The "renaissance" of radio astronomy

Chiara Ferrari

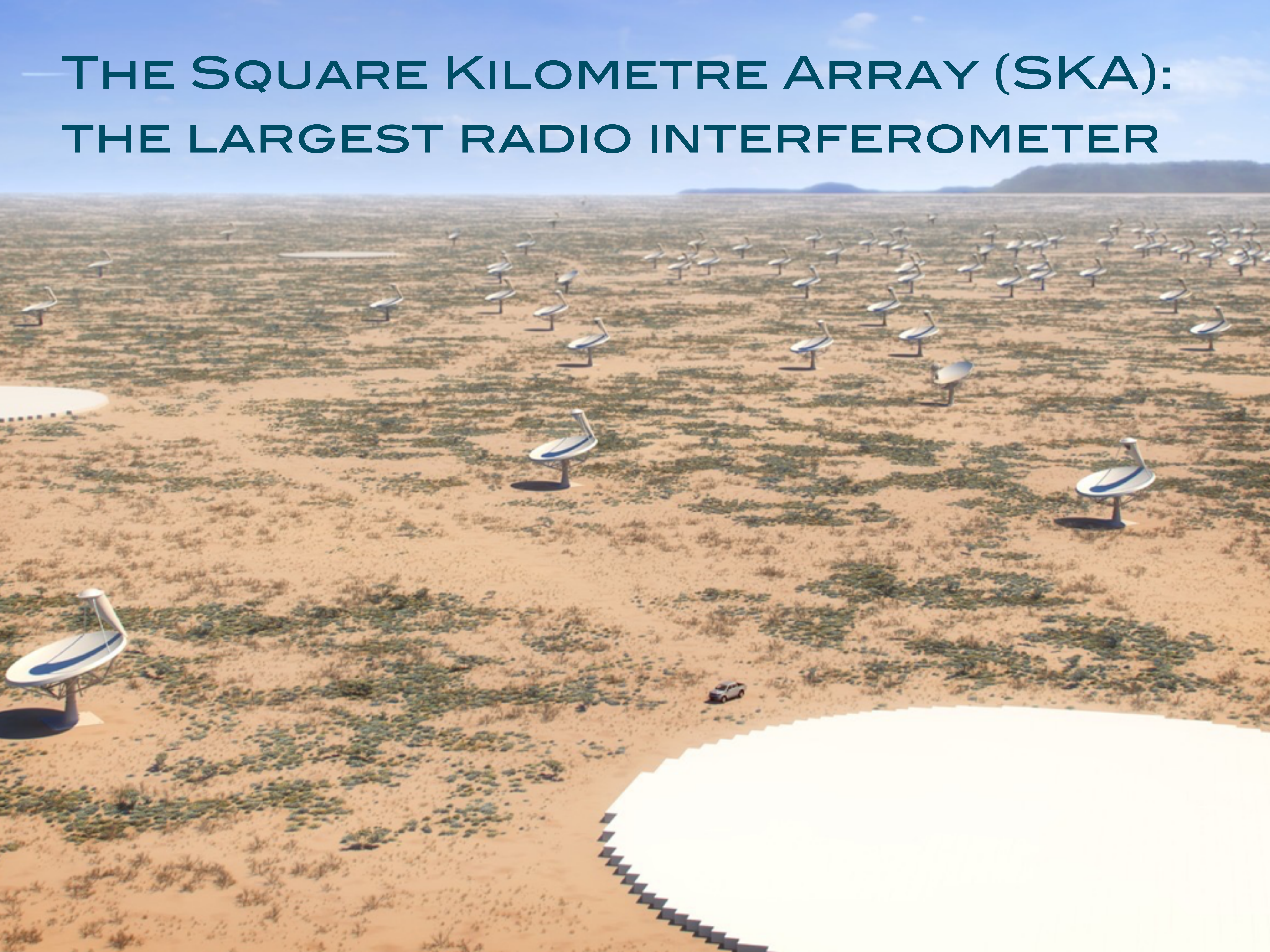
(OCA, Lagrange)

Image courtesy:
www.skatelescope.org

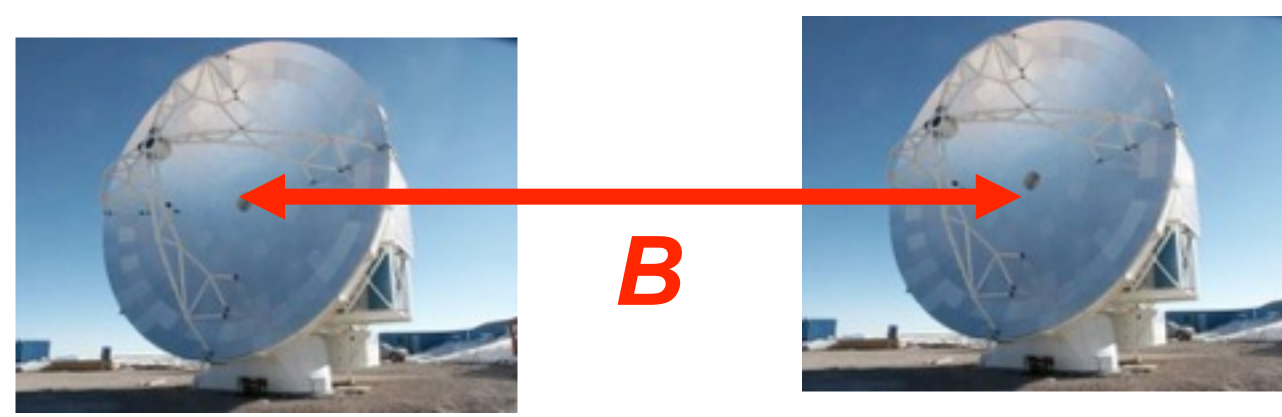
Overview of the talk

- Why interferometry?
- The Square Kilometre Array: the telescope and the project
- SKA pathfinders and precursors: the golden age of radio astronomy
- On-going and future radio surveys: the full sky at high-sensitivity
- A science case: galaxy clusters at radio wavelengths

The Square Kilometre Array (SKA): the largest radio interferometer



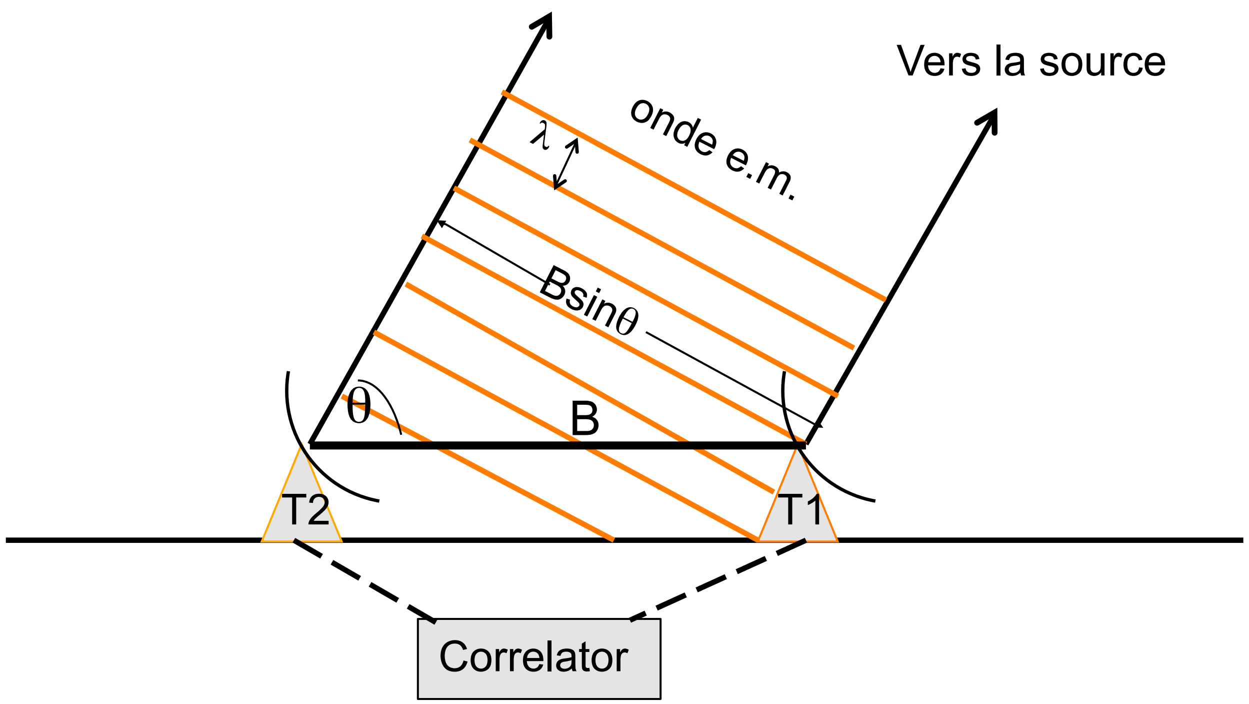
Why interferometry?

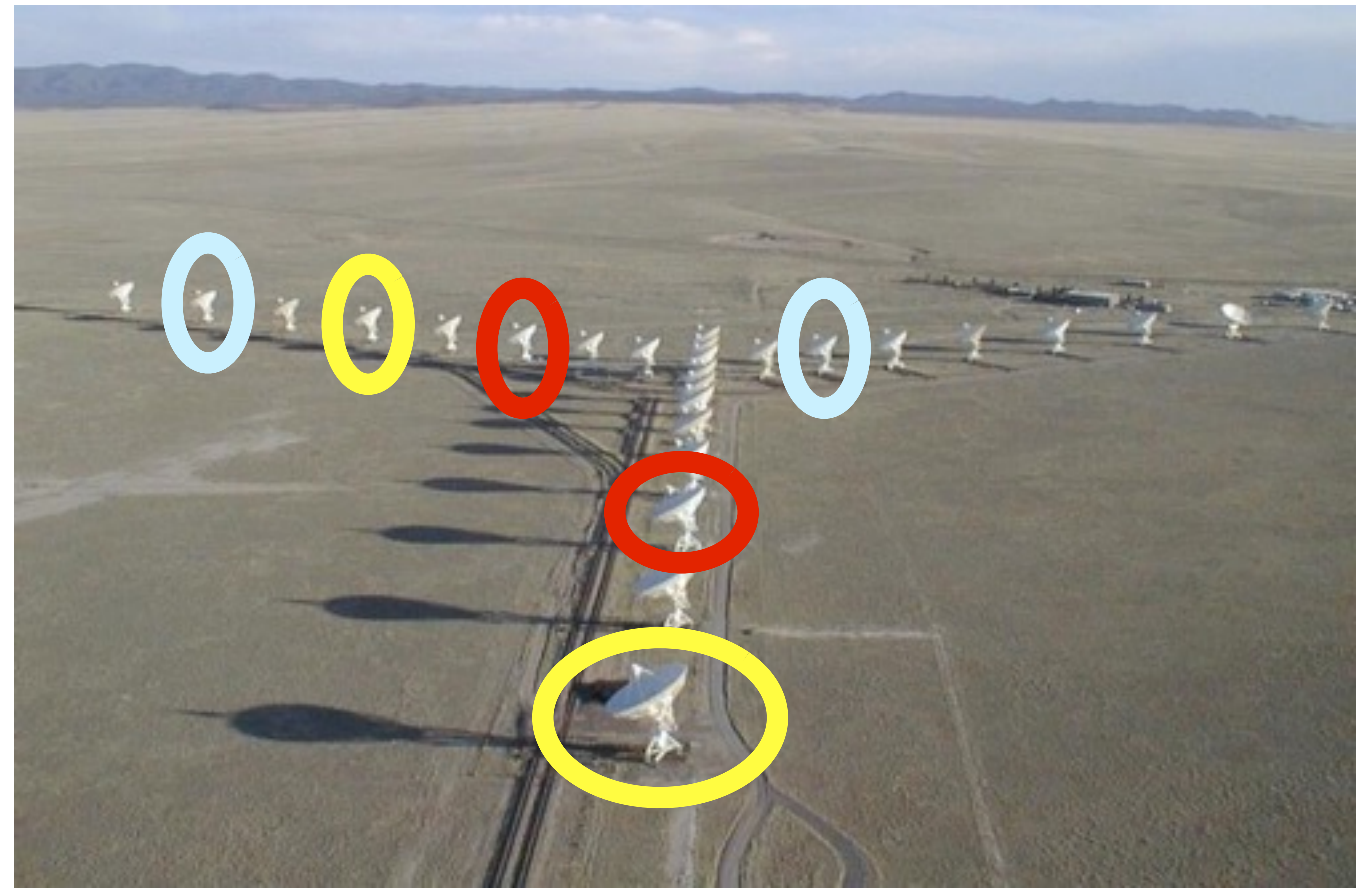


Angular resolution: $\theta = \lambda/D$

Angular resolution: $\theta = \lambda/B$

Why interferometry?

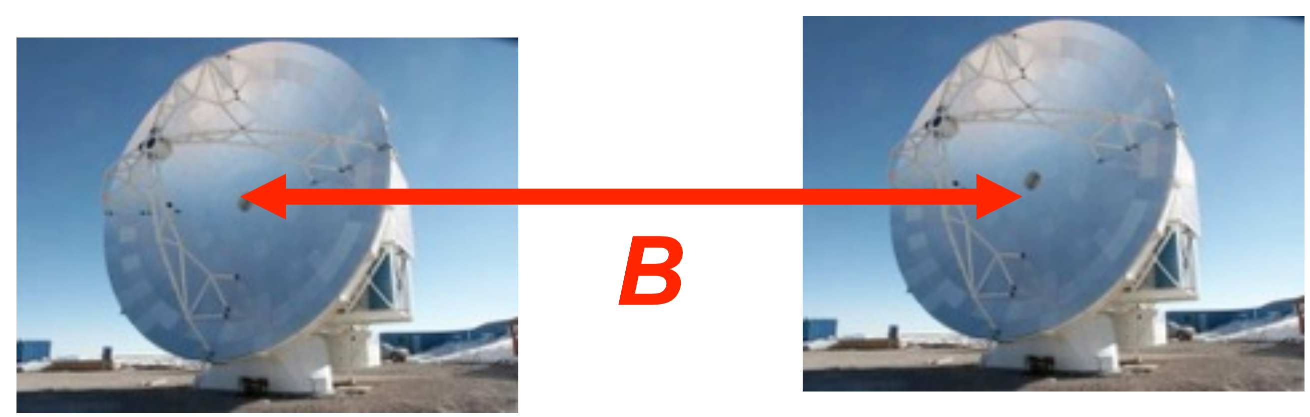




One visibility
for each couple of antennae

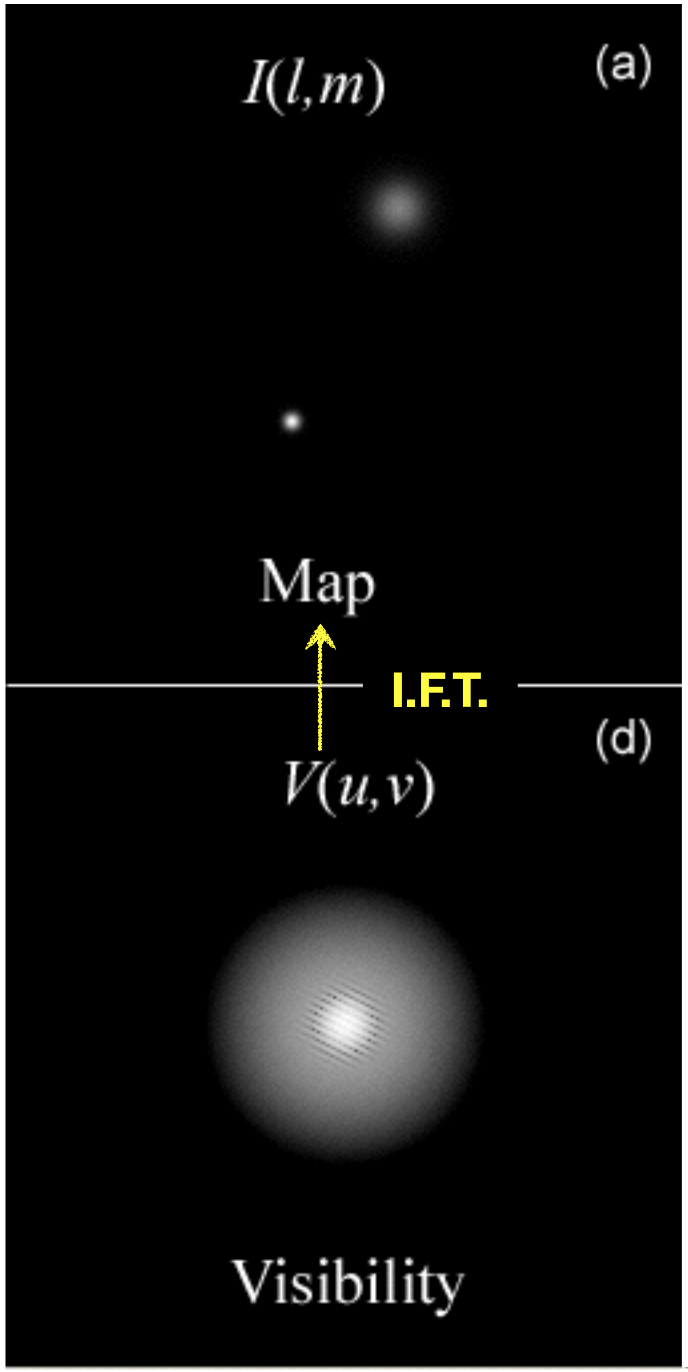
↓ **I.F.T.**

Sky Image

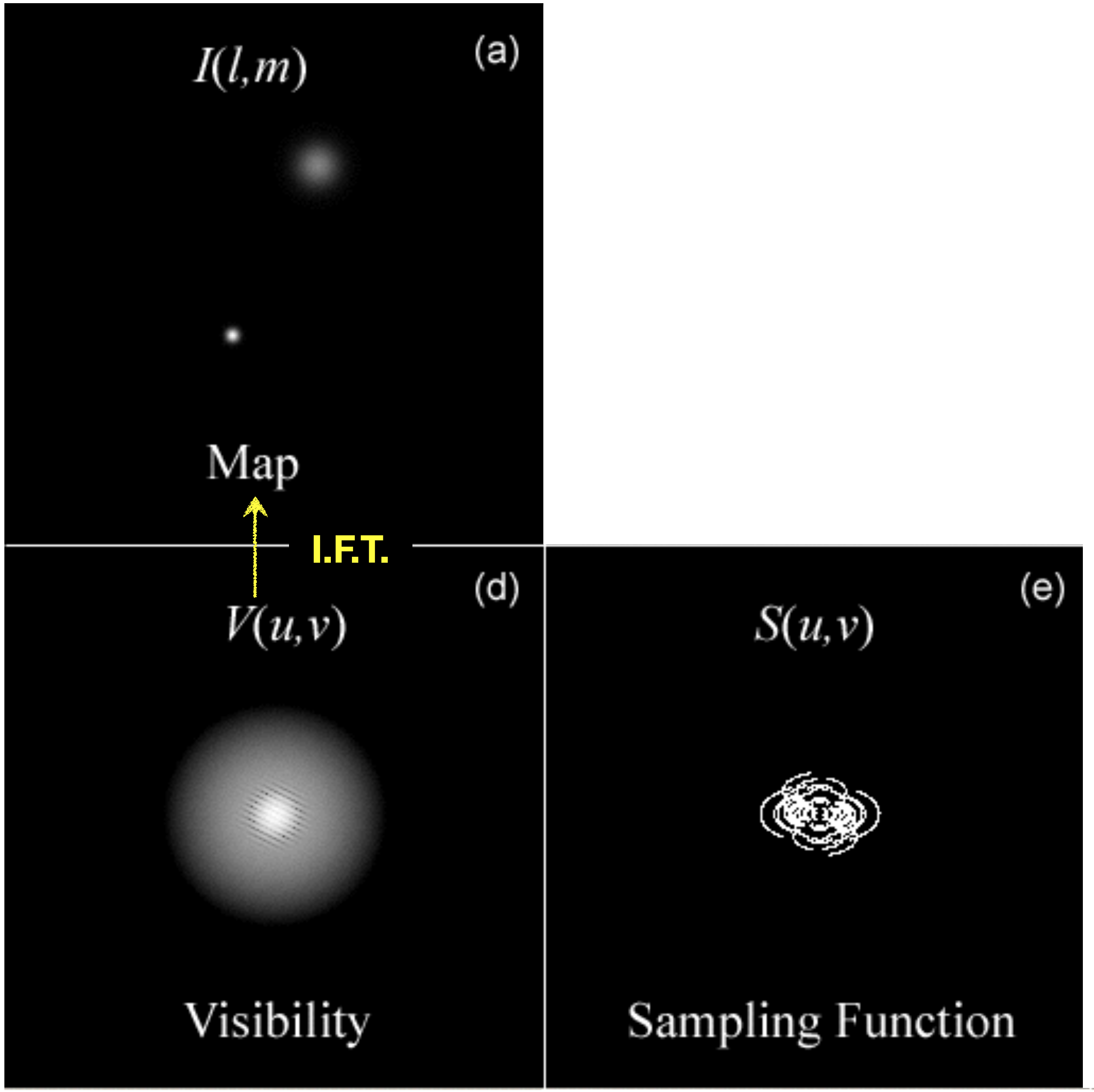


Angular resolution: $\theta = \lambda / B$

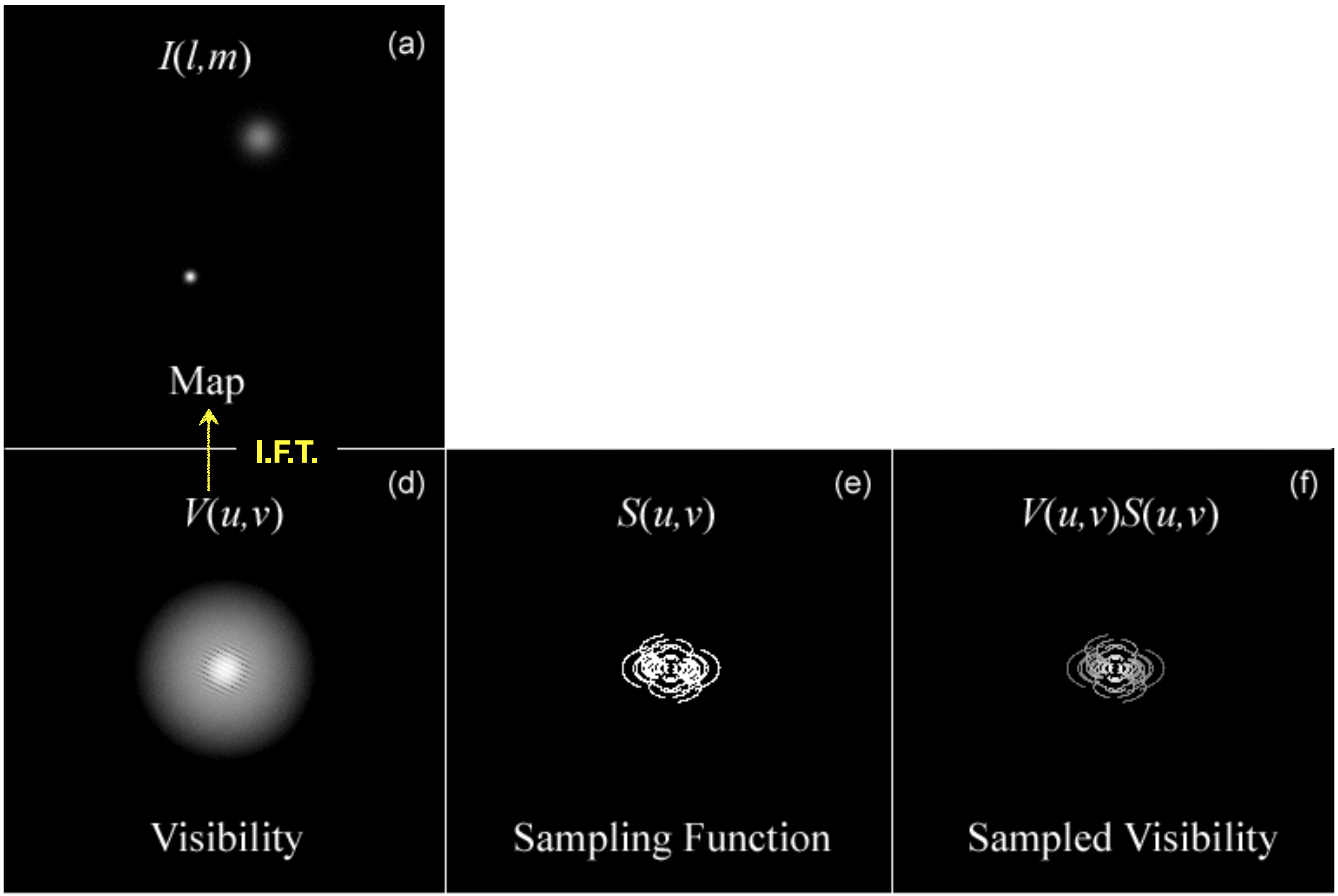
From visibilities to radio images



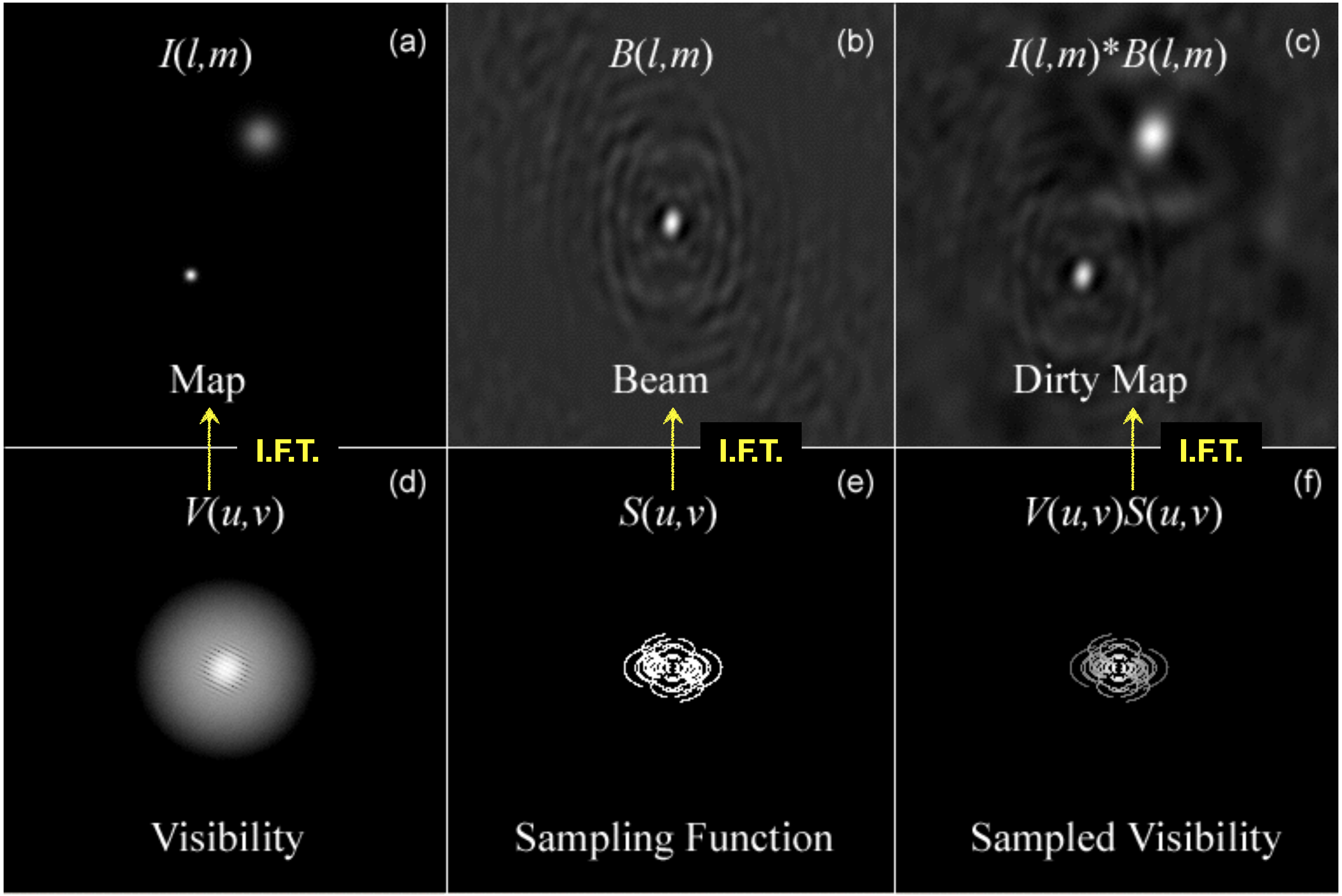
From visibilities to radio images



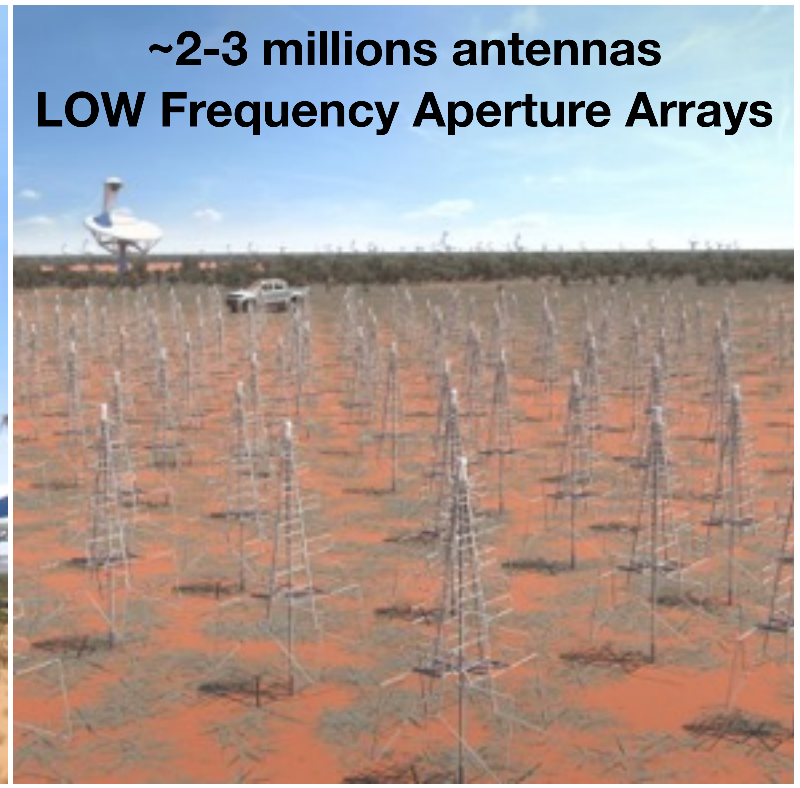
From visibilities to radio images



From visibilities to radio images

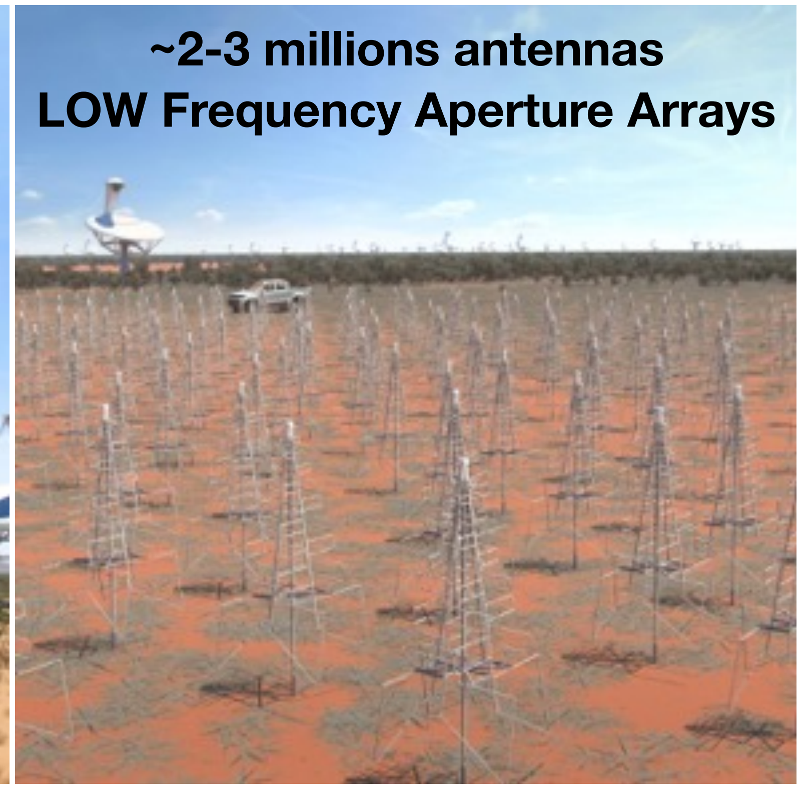


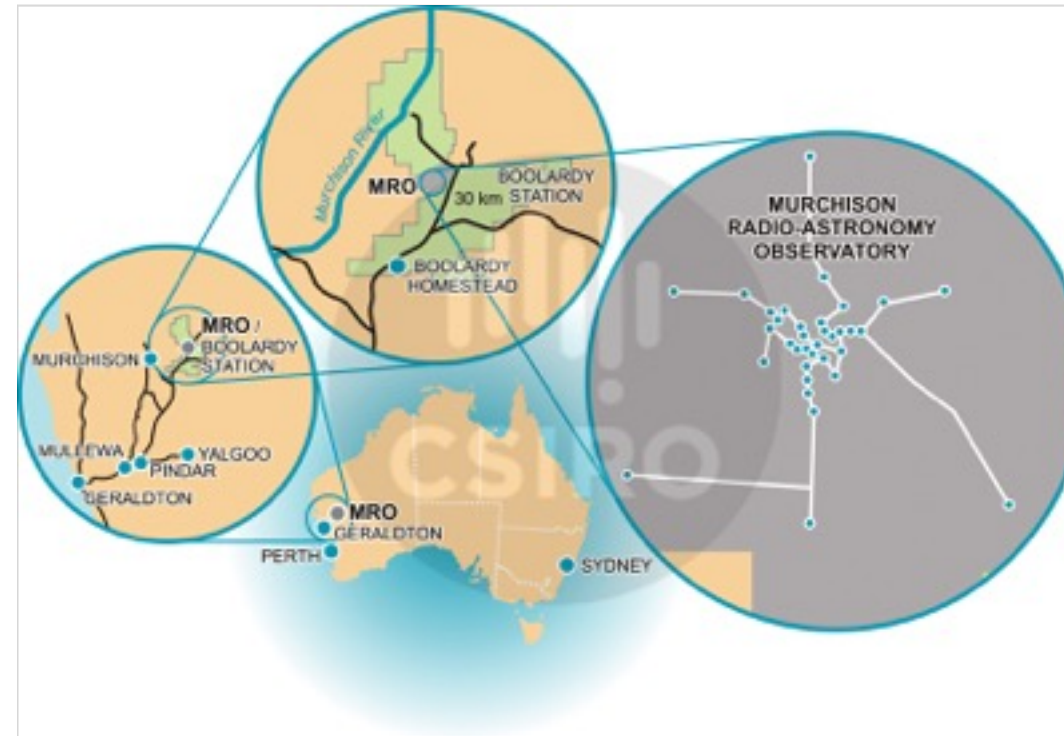
The Square Kilometre Array (SKA)



- A collecting area of 1 km^2
- Observing from 50 MHz to ≥14 GHz
- Sub-arcsec angular resolution
- FoV of several deg^2

THE SQUARE KILOMETRE ARRAY (SKA)



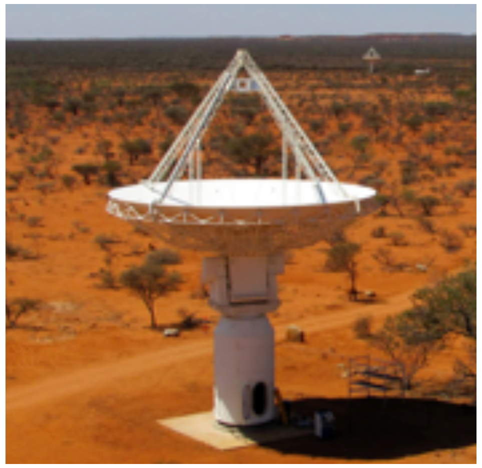


- A collecting area of 1 km^2
- Observing from 50 MHz to ≥14 GHz
- Sub-arcsec angular resolution
- FoV of several deg^2

The precursors

MeerKAT

- Location: South Africa
- Max baseline: 8 km
- Frequency coverage: 0.5 - 10 GHz
- Number of antennas: 64
- Diameter of antennas: 13.5 m
- Fully operational from 2017



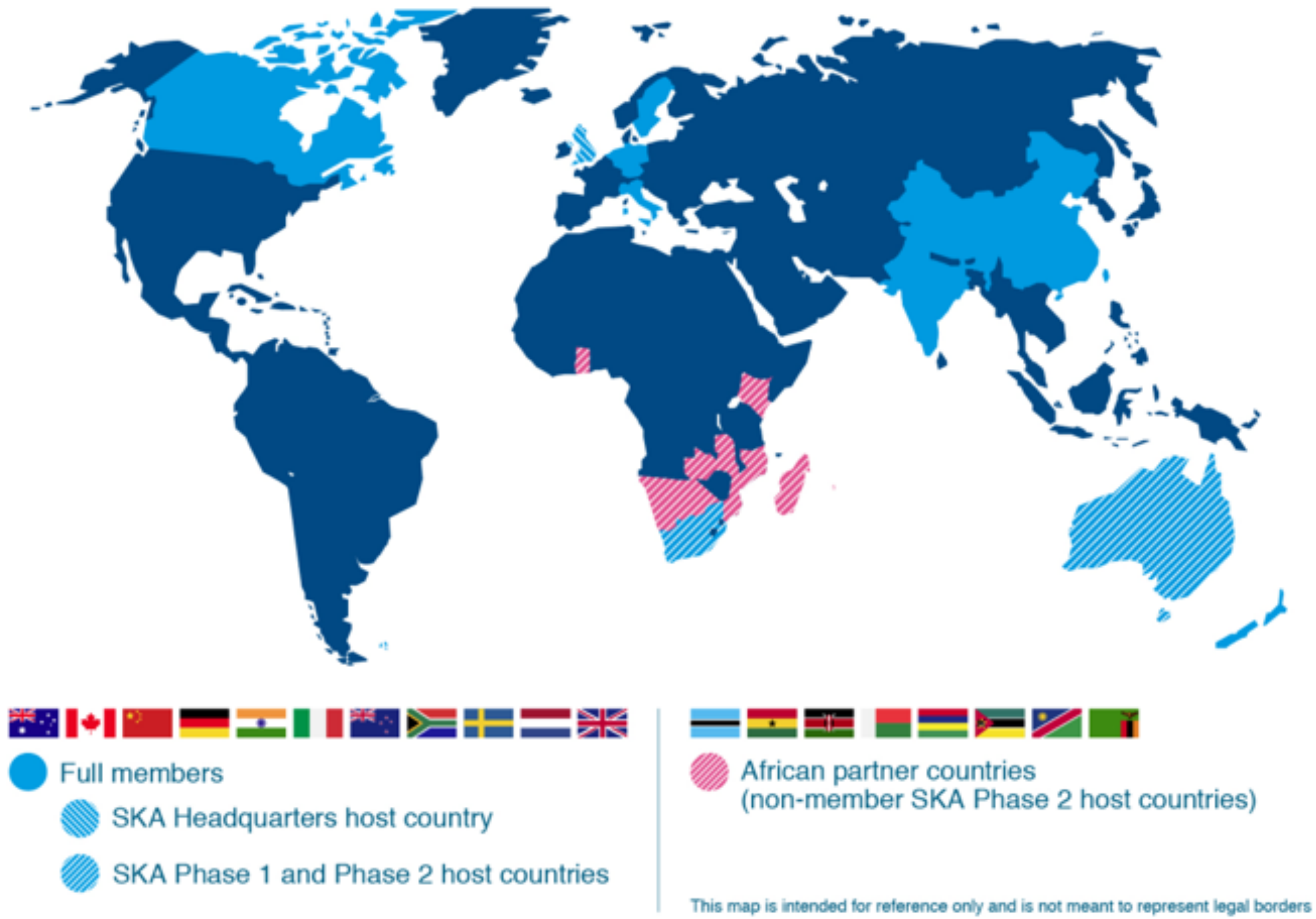
ASKAP

- Location: Australia
- Max baseline: 6 km
- Frequency coverage: 0.7 - 8 GHz
- Number of antennas: 36
- Diameter of antennas: 12 m
- Fully operational from 2016

MWA

- Location: Australia
- Max baseline: 3 km
- Frequency coverage: 80 - 300 MHz
- Number of stations: 128
- Antennas per station: 16
- Fully operational since 2012

SKA members & governance



- **UK Company Limited by Guarantee**
- **Expedient solution to enable SKA project to proceed; long-term governance structure under review – studying establishing a treaty organisation**

The SKA Headquarters

The SKA Headquarters

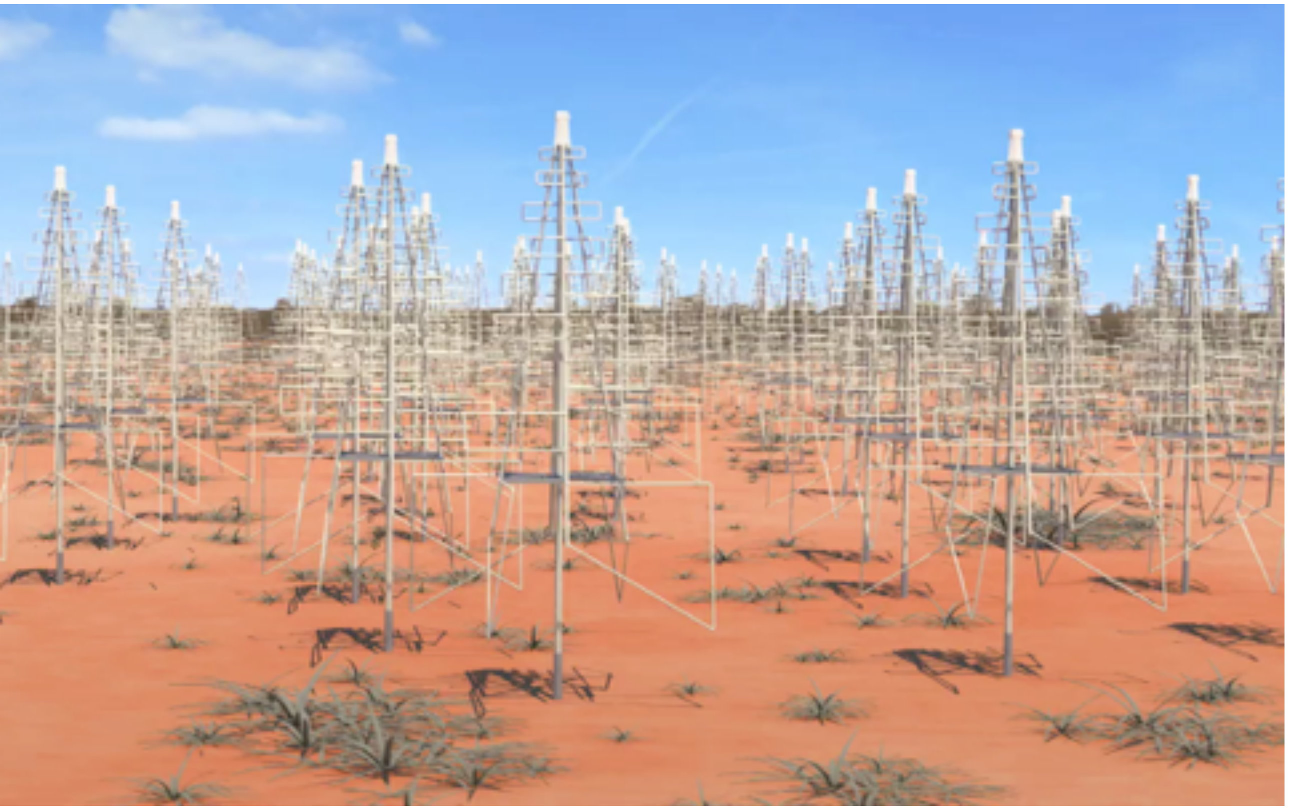
SKA-Mid: ~ 190 15m dishes + MeerKAT, RSA

Courtesy: Phil Diamond

SKA Phase 1

2 sites (South Africa, Australia);
3 telescopes; one Observatory
Frequency range SKA1: 50 MHz – 14 GHz

Cost-cap: €650M
Construction: 2017 – 2023
Early science: 2020
Phase 2 SKA: 2023 - 2030



SKA-Low: ~ 260,000 low-freq dipoles, AUS

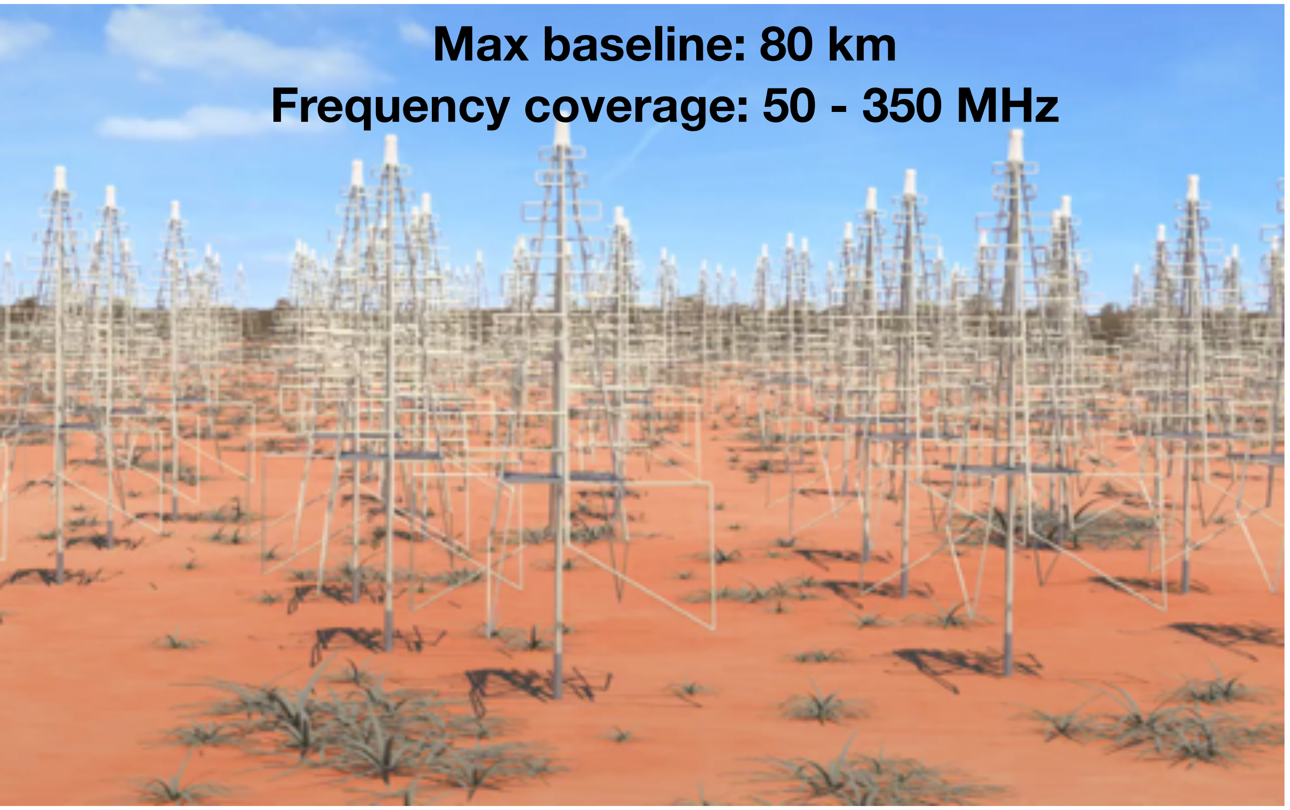
SKA-Survey: ~ 60 15m dishes + ASKAP, AUS

Re-baselining (I)

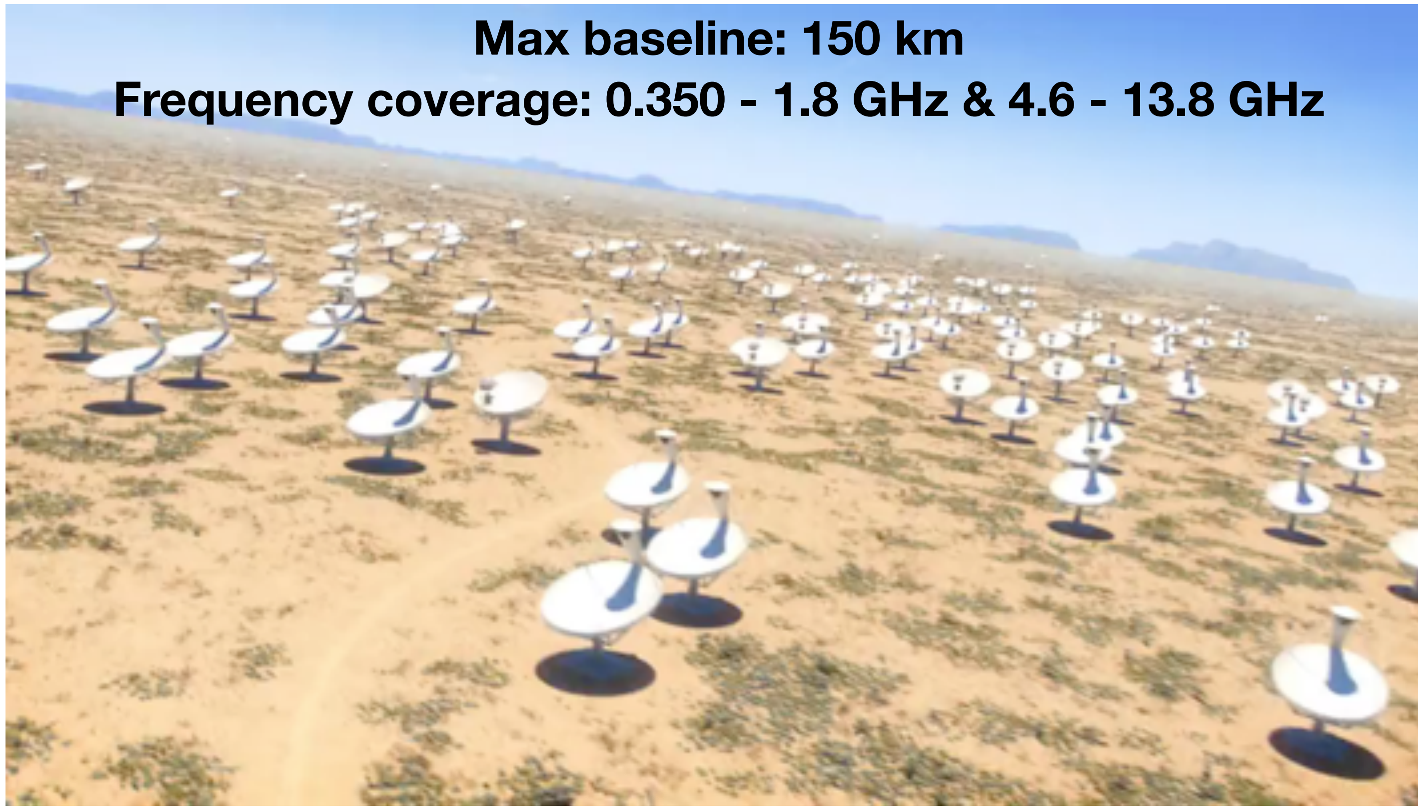
• *SKA1-Mid in South Africa should be built, incorporating MeerKAT. 70% of the planned 190 SKA1 dishes should be constructed with a target of delivering baseline lengths of 150km, but with a fallback of 120km if funding is constrained. Receiver bands 2, 5 and 1 should be constructed for all SKA1-Mid dishes, with their priority order as written. Capability to form and process 50% of the planned pulsar search beams should be delivered.*

• *SKA1-Low in Australia should be built. 50% of the planned 262,144 low frequency dipoles should be deployed. The array should cover the frequency range 50-350 MHz, as planned. The current planned baseline lengths of ~80km should be retained. The inclusion of a pulsar search capability for SKA1-Low (currently an Engineering Change Proposal on hold) should be actively explored.*

• *SKA1-Survey in Australia should be deferred.*



SKA-Low: 50% of the 260,000 low-freq dipoles, AUS



SKA-Mid: 70 % of the 190 15m dishes + MeerKAT, RSA

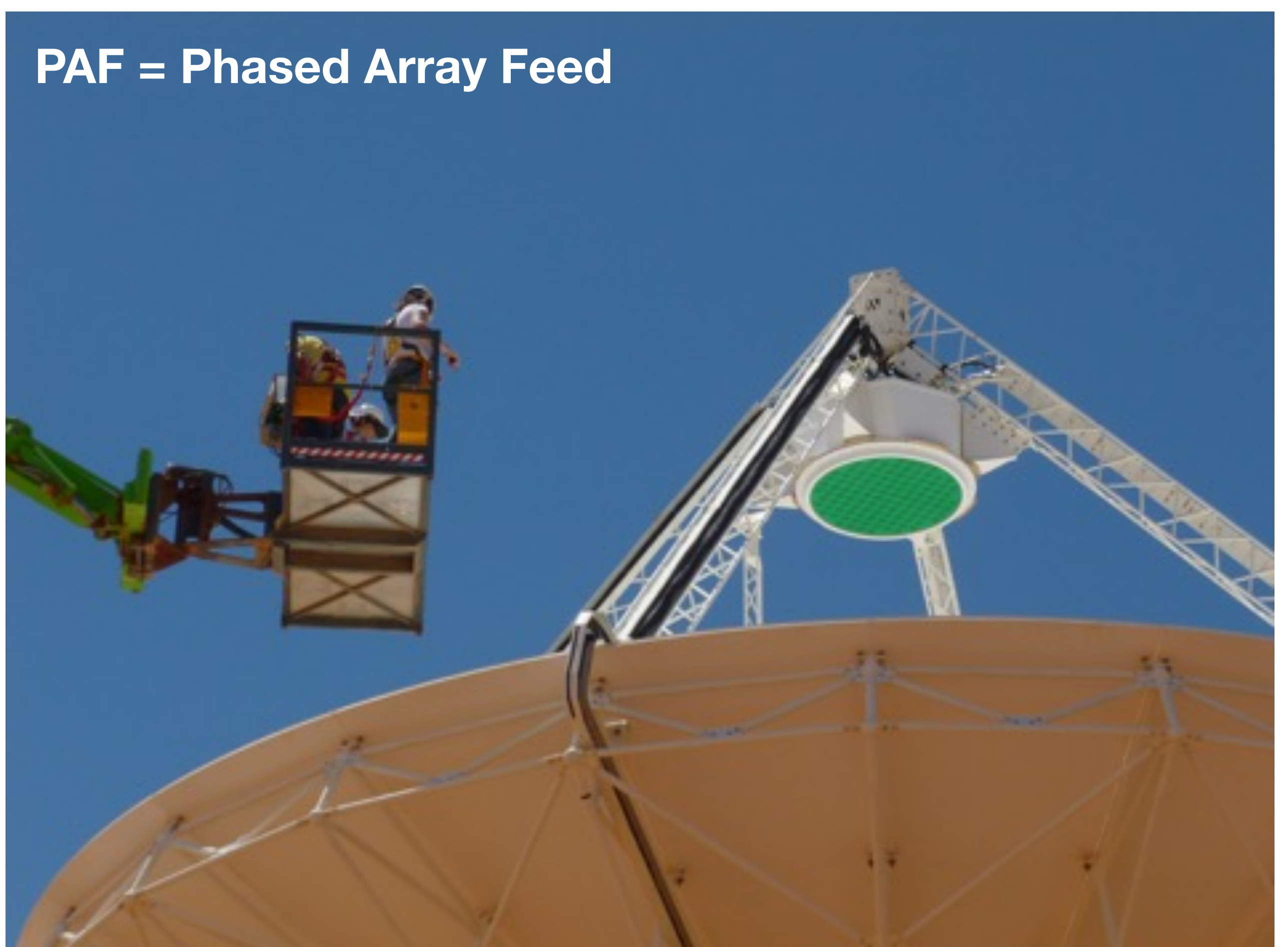
Re-baselining (II)

It is also recommended that the Board approve funding, with Australia's agreement, for the operations of ASKAP as an integral component of SKA1; the start date to be negotiated with Australia. This would enable ASKAP to provide SKA1 with an early survey capability and also serve as a platform for the development of next-generation PAFs.

SKAO will immediately implement the variations in the design via a series of Engineering Change Proposals, which would require full documentation and review through our now standard processes. A new Baseline Design document will be generated for consideration at the July 2015 Board meeting.

Phil Diamond March 2015

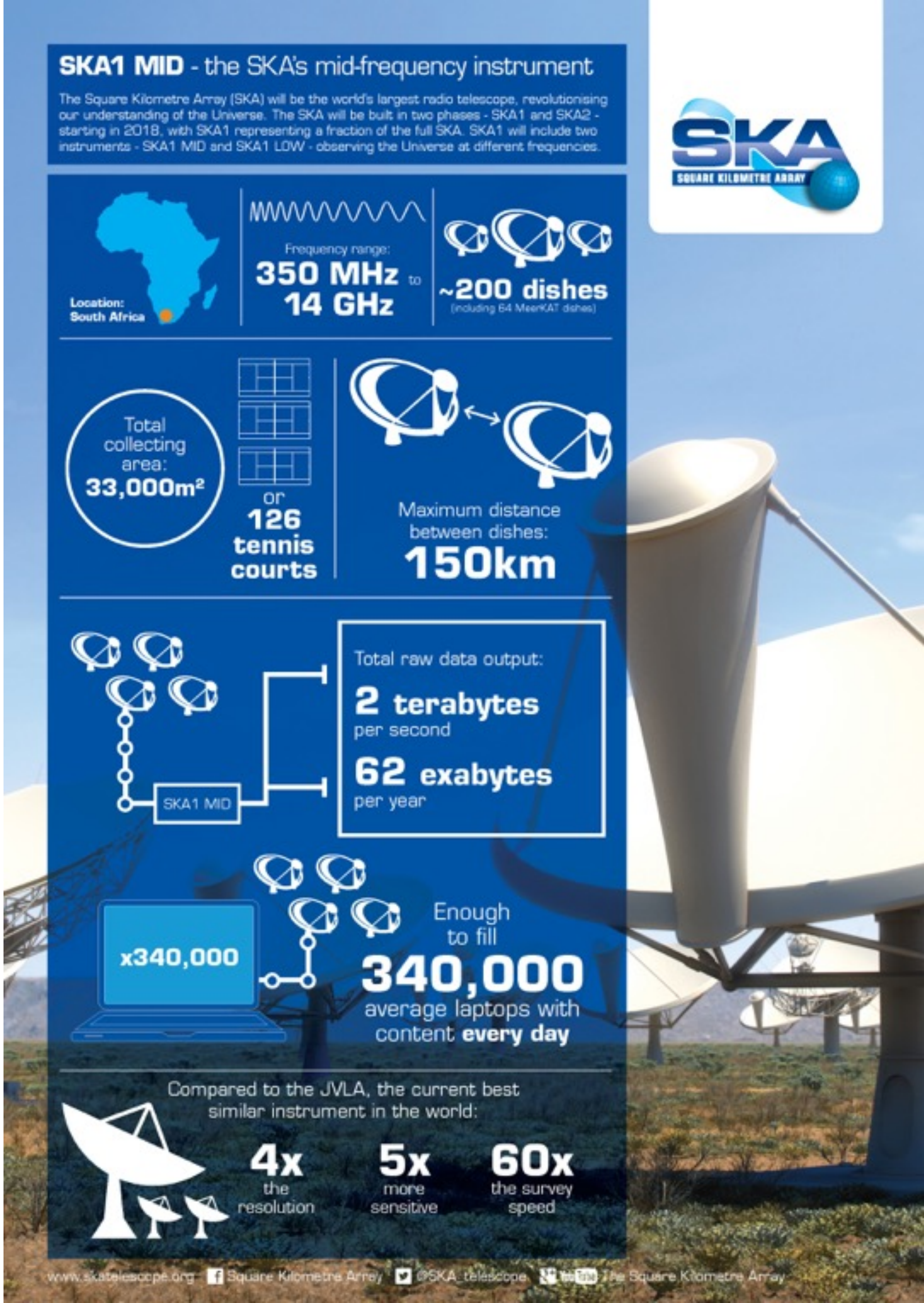
Max baseline: 6 km
Frequency coverage: 0.700 - 1.8 GHz
FoV: 30 square degree@1.4 GHz



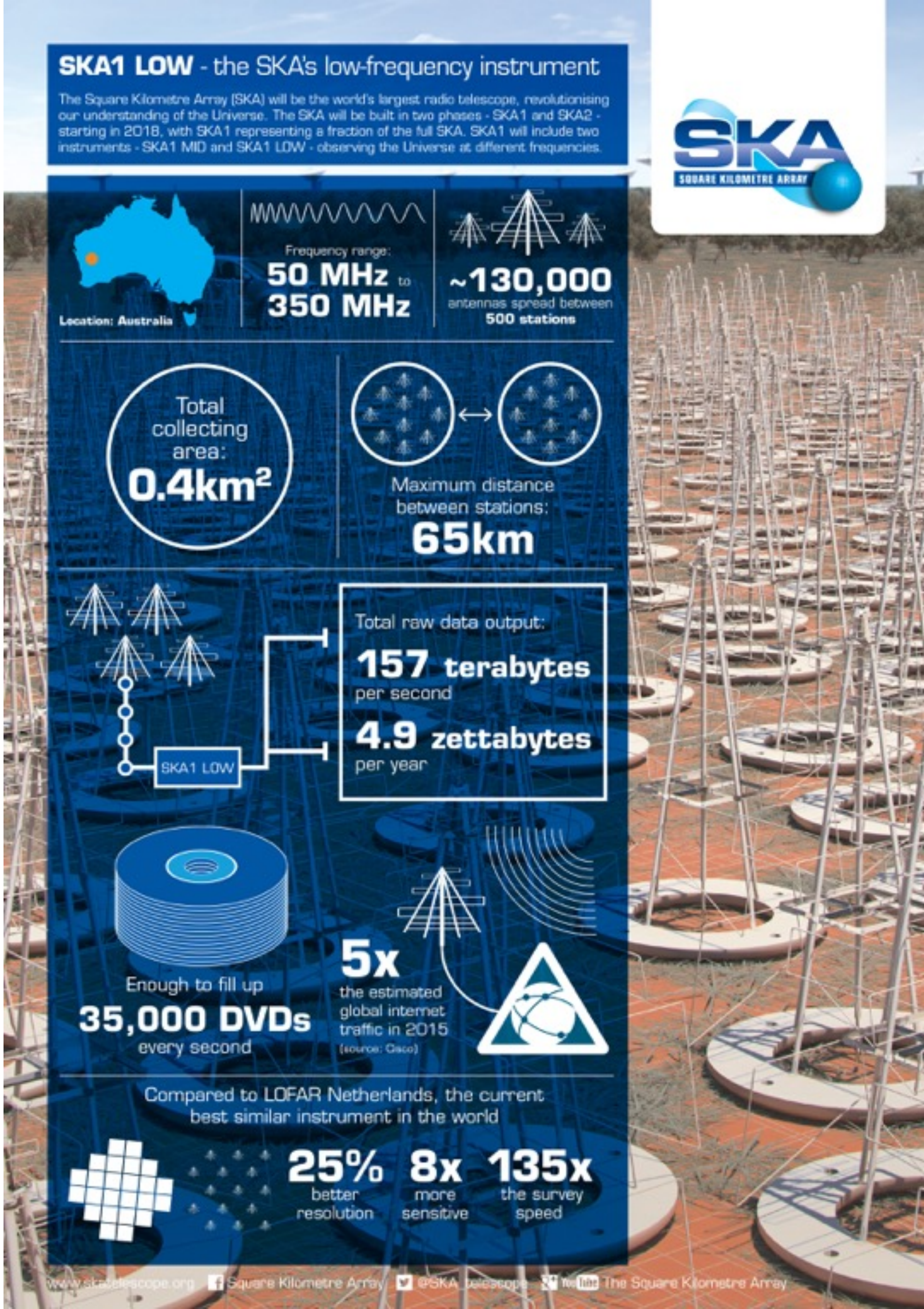
PAF = Phased Array Feed

ASKAP: 36 12m dishes, AUS

SKA Processing Challenge



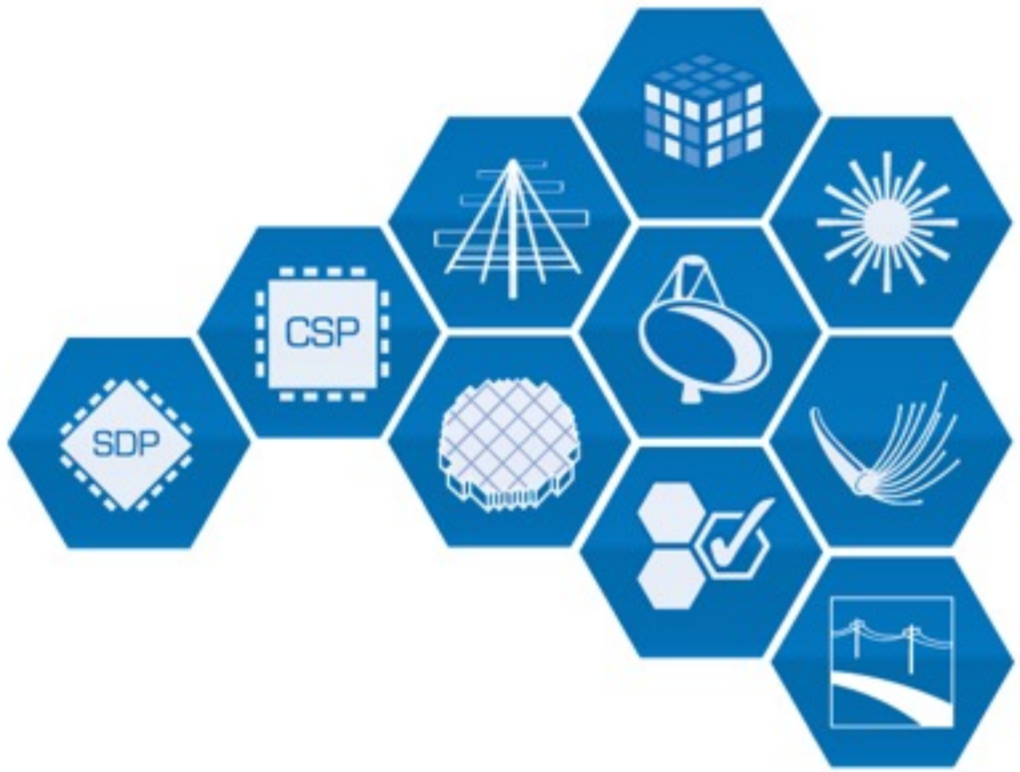
SKA Processing Challenge



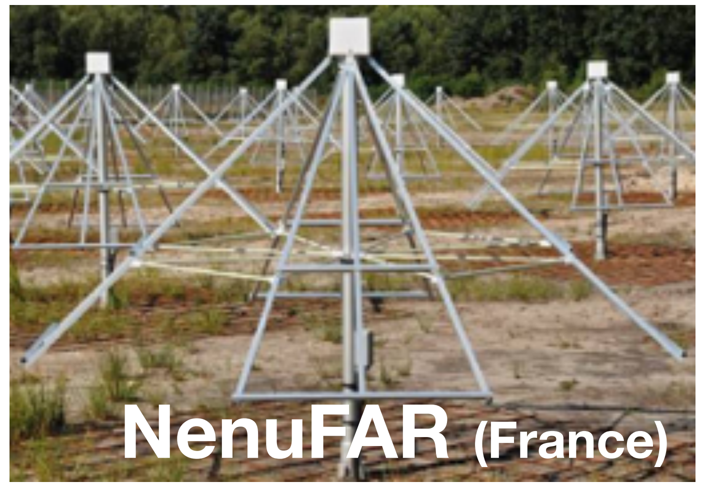
Preparation process to the SKA

SKA Work Packages

- Assembly, Integration and Verification (AIV)
- Central Signal Processor (CSP)
- Dish (DSH)
- Infrastructure Australia & Africa (INFRA AU/SA)
- Low-Frequency Aperture Array (LFAA)
- Mid-Frequency Aperture Array (MFAA)
- Signal and Data Transport (SaDT)
- Signal Data Processor (SDP)
- Telescope Manager (TM)
- Wideband Single Pixel Feeds (WBSPF)



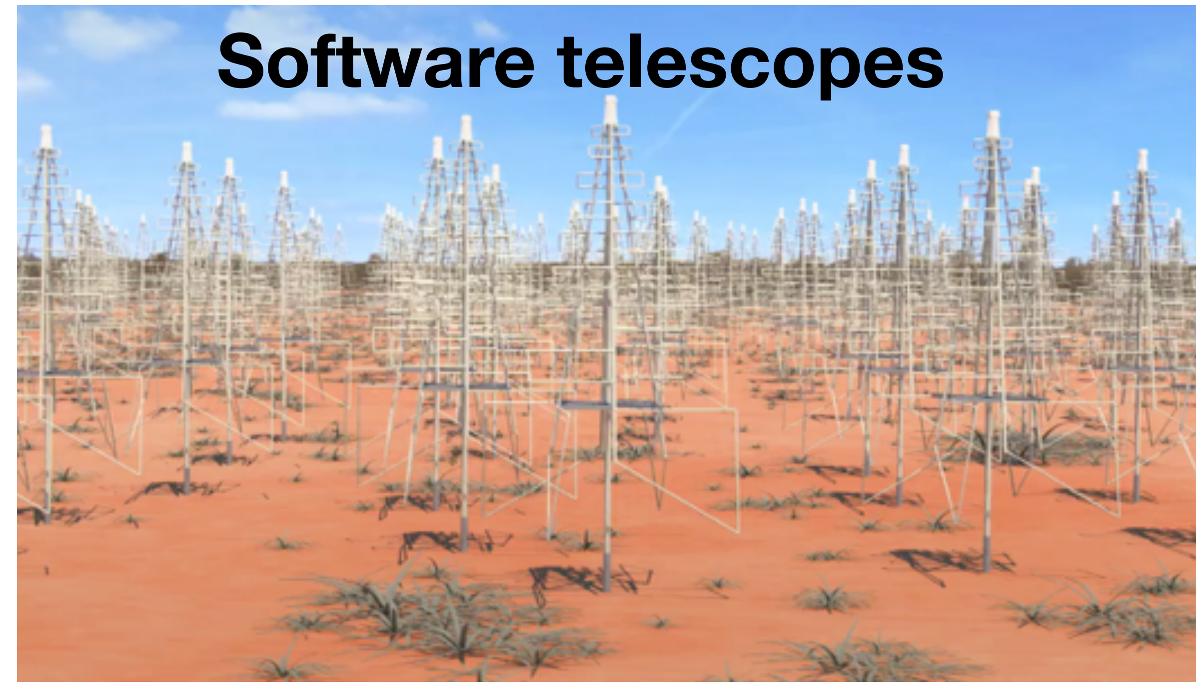
NOT ONLY PRECURSORS: THE SKA PATHFINDERS

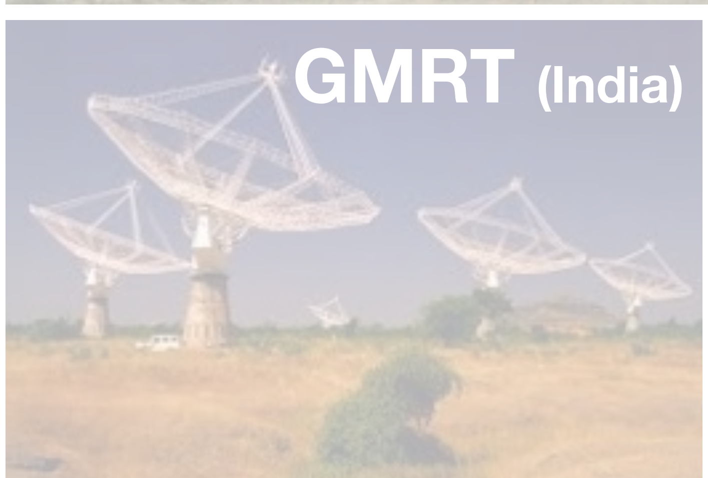


Precursor facility:
A telescope on one of the two candidate sites

Pathfinder:
SKA-related technology, science and operations activity

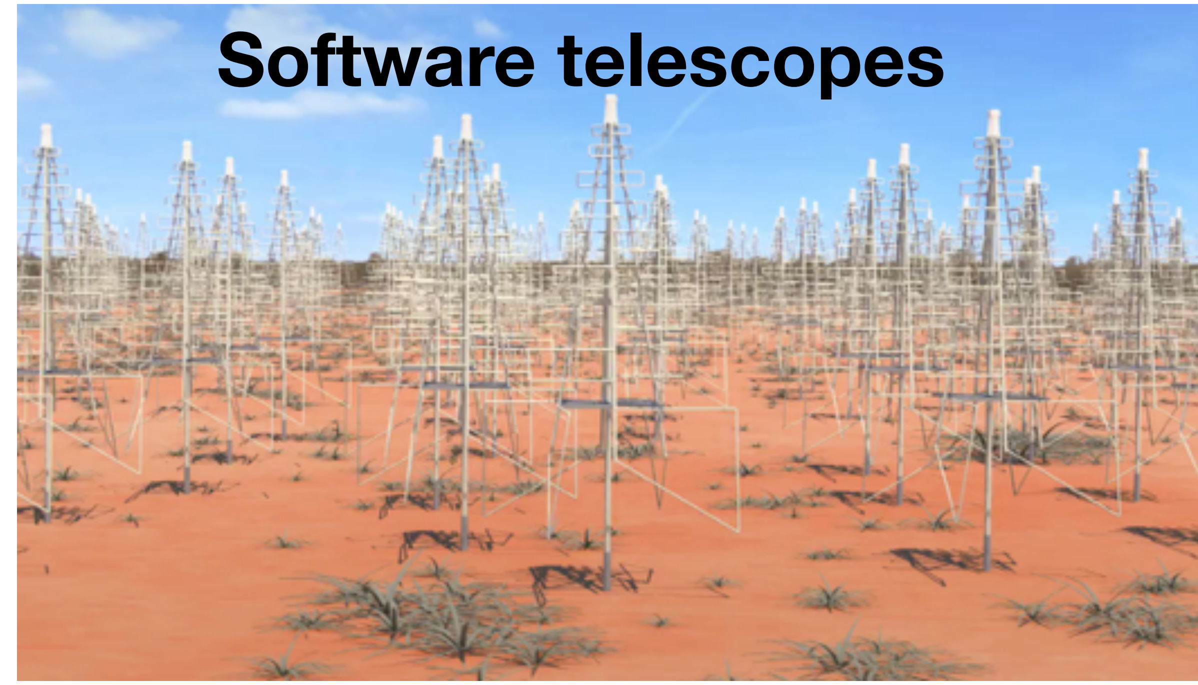
Not only precursors: the SKA pathfinders

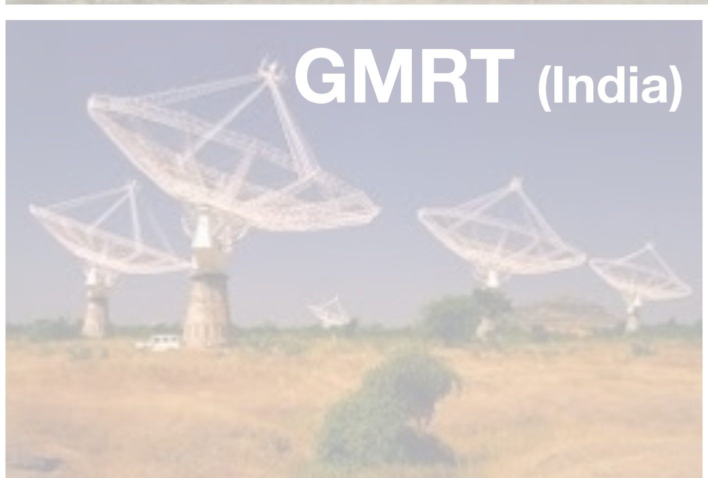




Pathfinder:
SKA-related technology, science and operations activity

Not only precursors: the SKA pathfinders

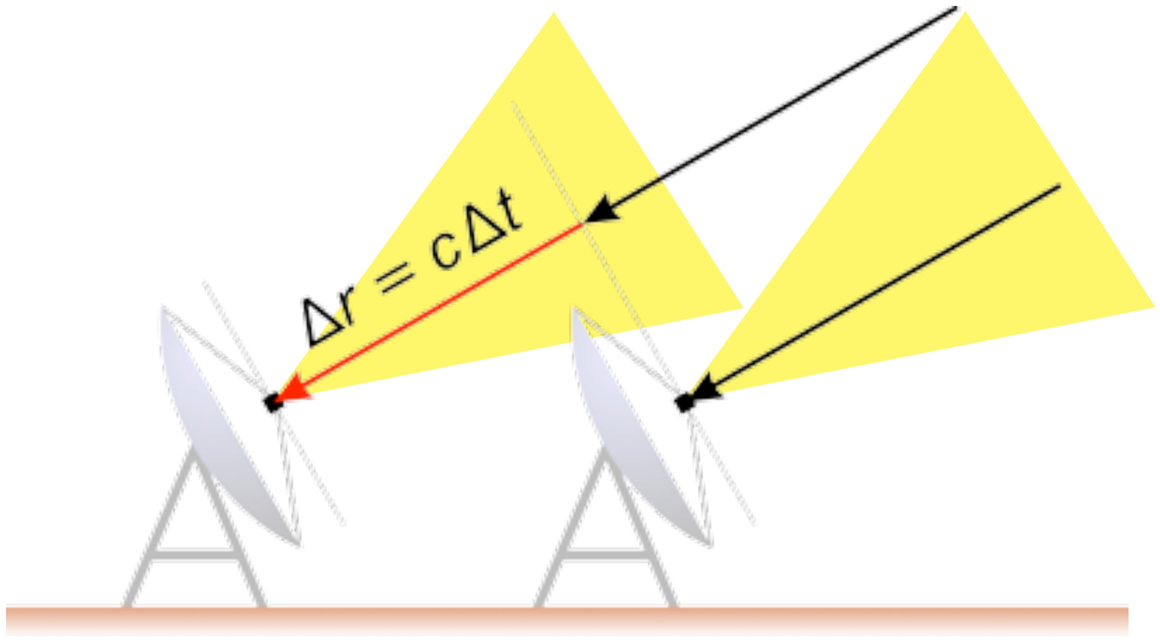


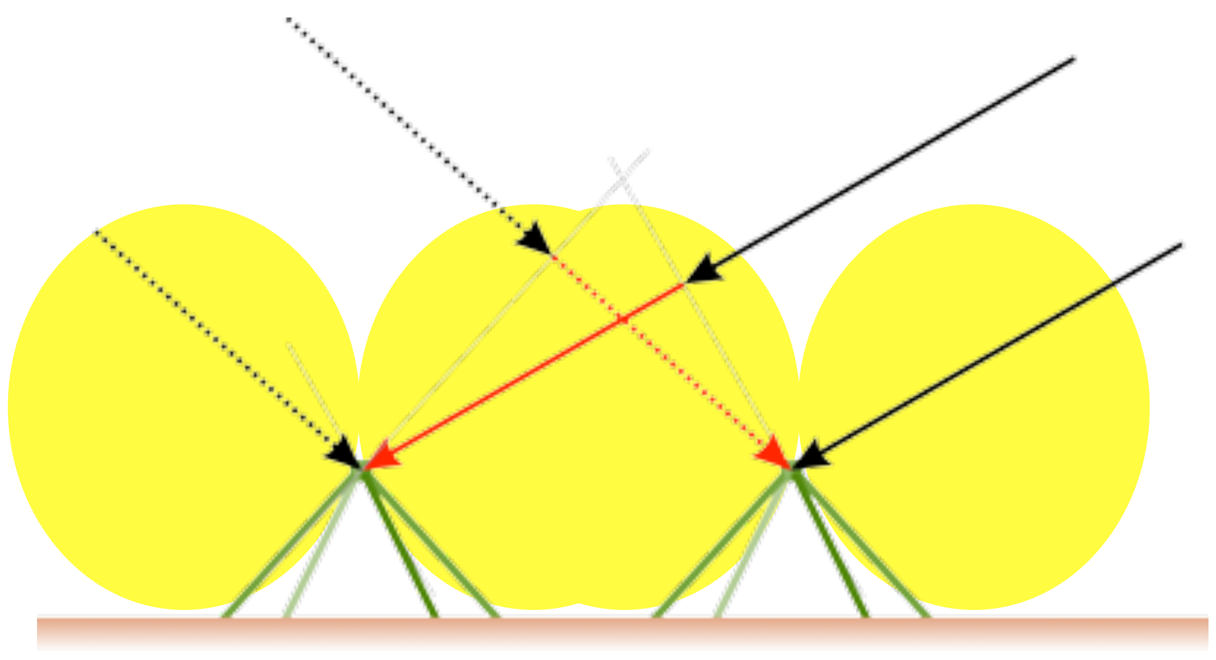


Pathfinder:
SKA-related technology, science and operations activity

LOFAR = Software Telescope

The field of view (FoV)





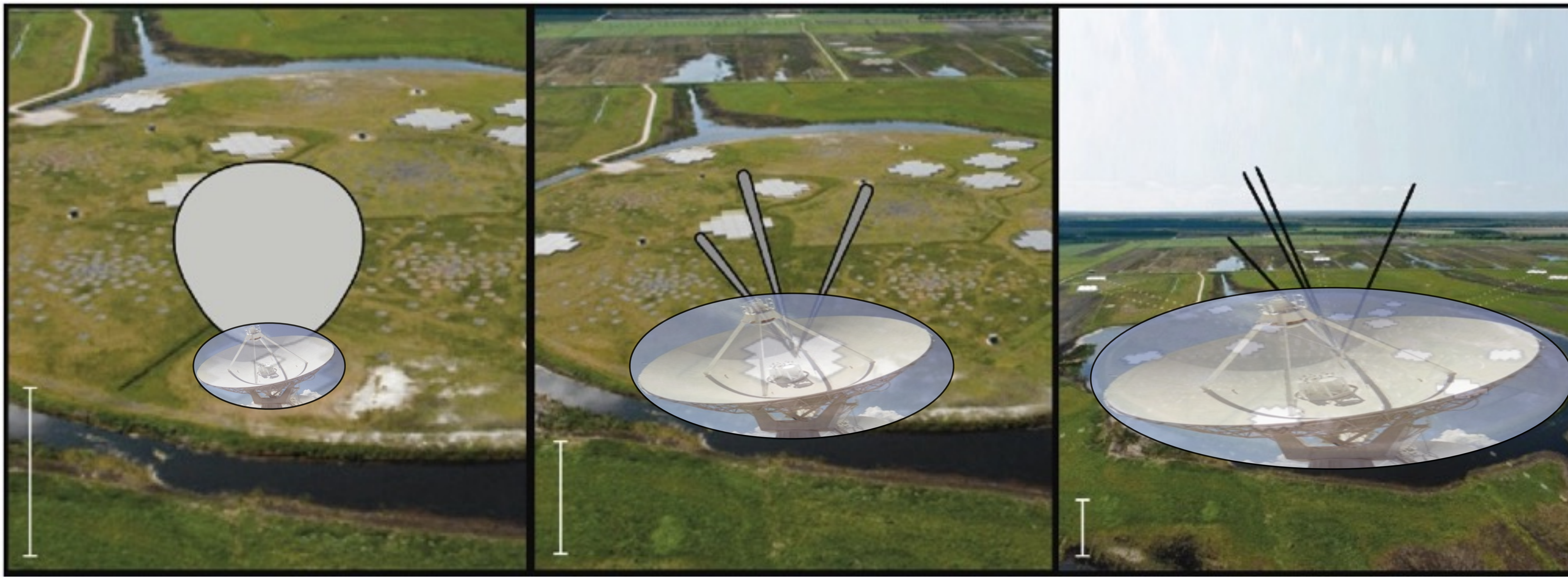
Old !

New !

LOFAR FoV (primary beam)

Stappers et al. 2011

LOFAR FoV (primary beam)

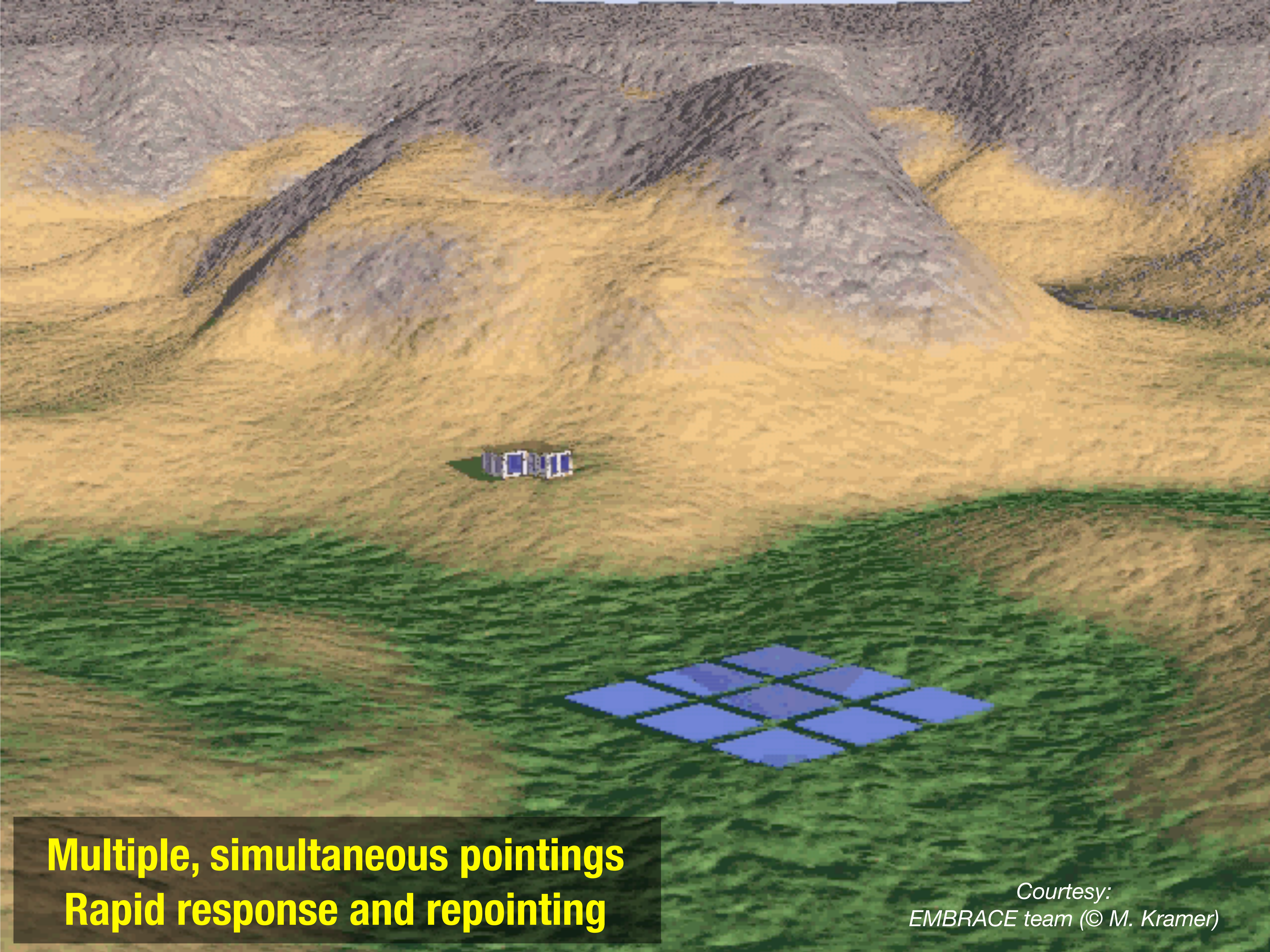


Stappers et al. 2011

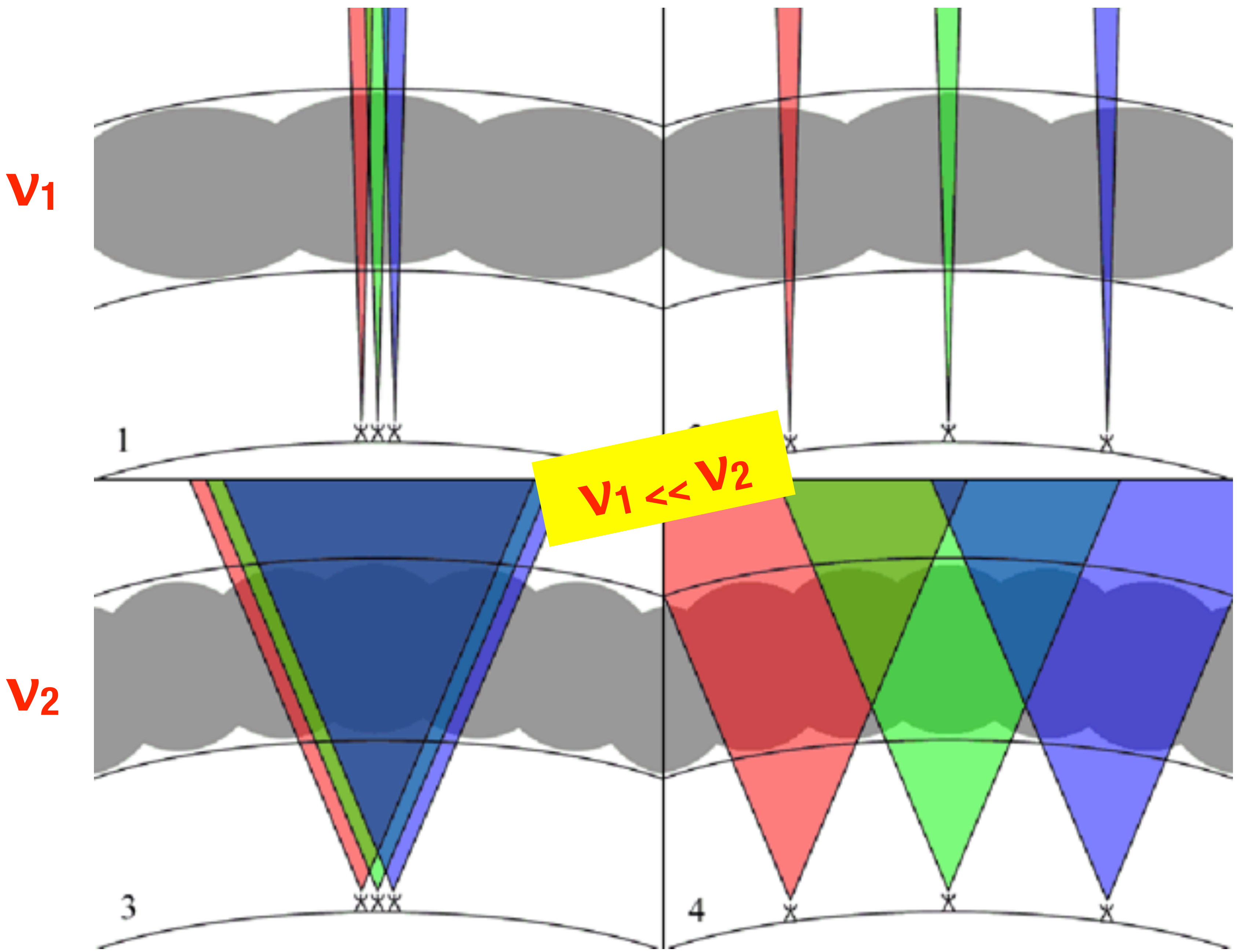

LOFAR Superterp
(The Netherlands)
LOFAR station
LOFAR station in Nançay


LOFAR Superterp
(The Netherlands)


LOFAR Superterp
(The Netherlands)
LOFAR ≡ software telescope


Multiple, simultaneous pointings
Rapid response and repointing
Courtesy:
EMBRACE team (© M. Kramer)

Direction Dependent Effects (DDE)



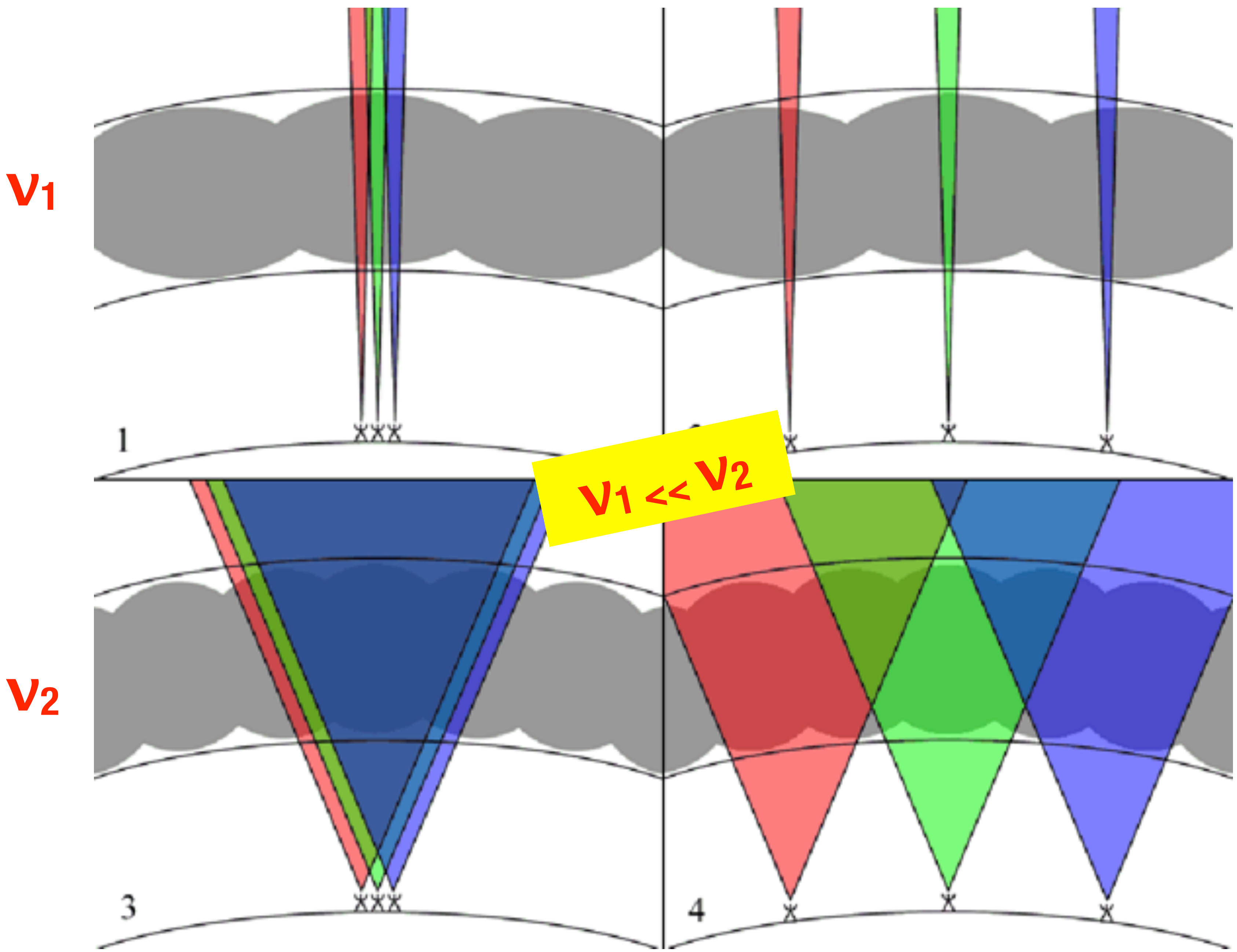
Intema et al. 2009

Ionosphere →

Random fluctuations of the refractive index →

Distorsions of the original wave front

Direction Dependent Effects (DDE)



Intema et al. 2009

Ionosphere →

Random fluctuations of the refractive index →

Distorsions of the original wave front

Field of View $\propto (\nu\, d)^{-1}$

Angular resolution $\propto (\nu\, D)^{-1}$

d = size of antennae

D = distance between antennae

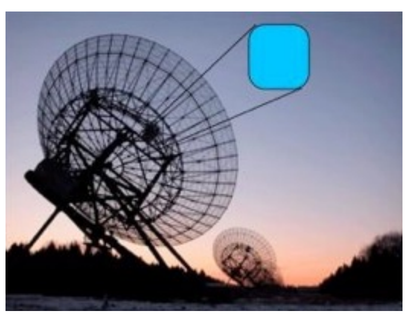
Direction & time dependent effects

Direction & time dependent effects

A wide frequency coverage

LOFAR
Europe
30-80 MHz +
110-240 MHz

MWA
Australia
80 - 300 MHz



APERTIF
The Netherlands
1000 - 1750 MHz

ASKAP
Australia
700 - 1800 MHz

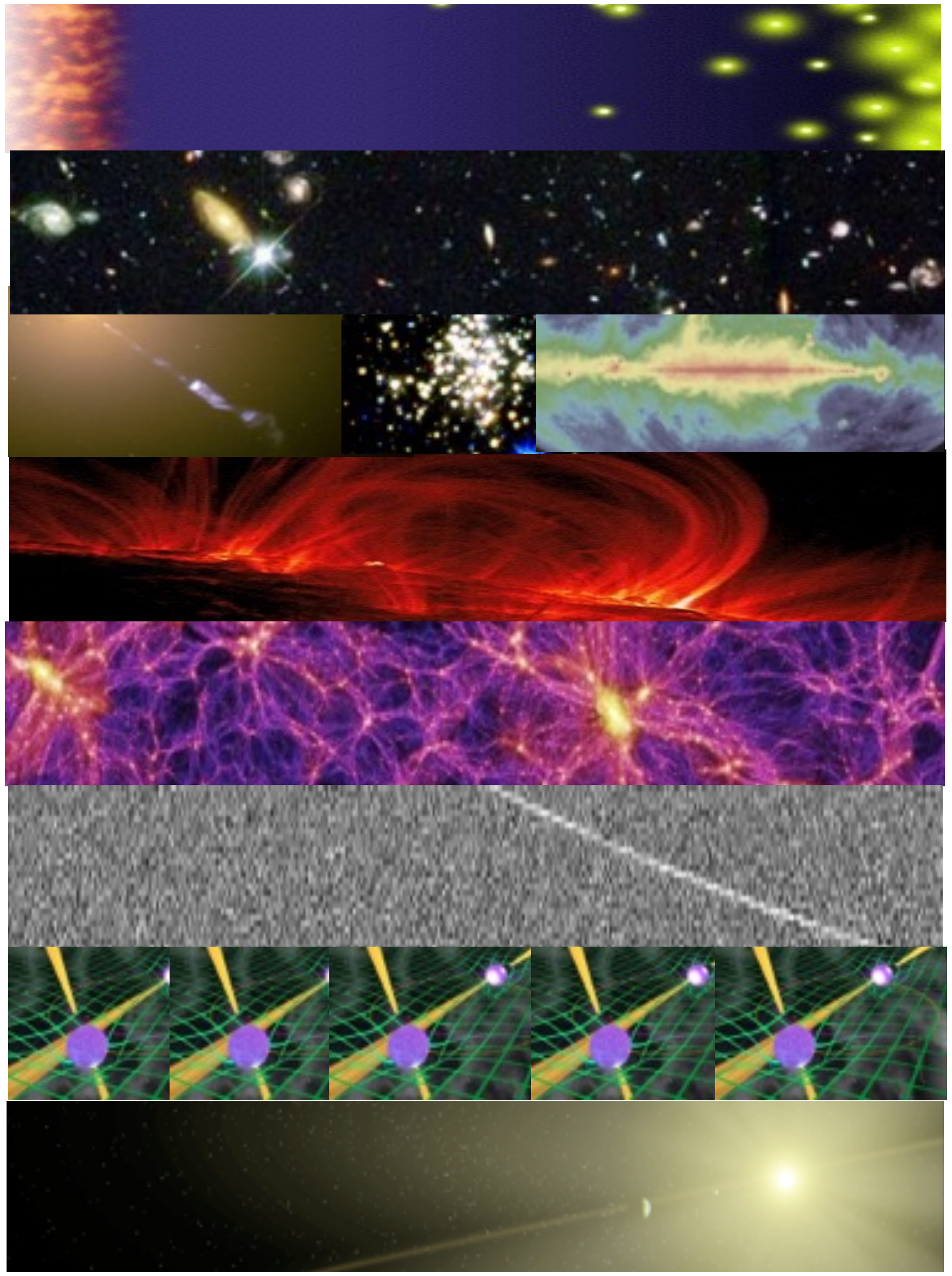
MeerKAT
South Africa
1000 - 1750 MHz

SKA
Australia / South Africa
~ 50 MHz - 15 GHz

Preparation process to the SKA

SKA Science Working Groups

- Epoch of Reionisation & the Cosmic Dawn
- Galaxy Evolution – HI
- Galaxy Evolution – Continuum
- Cosmic Magnetism
- Cosmology
- Transients
- Pulsars (“Strong field tests of gravity”)
- Astrobiology (“The Cradle of Life”)



Courtesy: Phil Diamond

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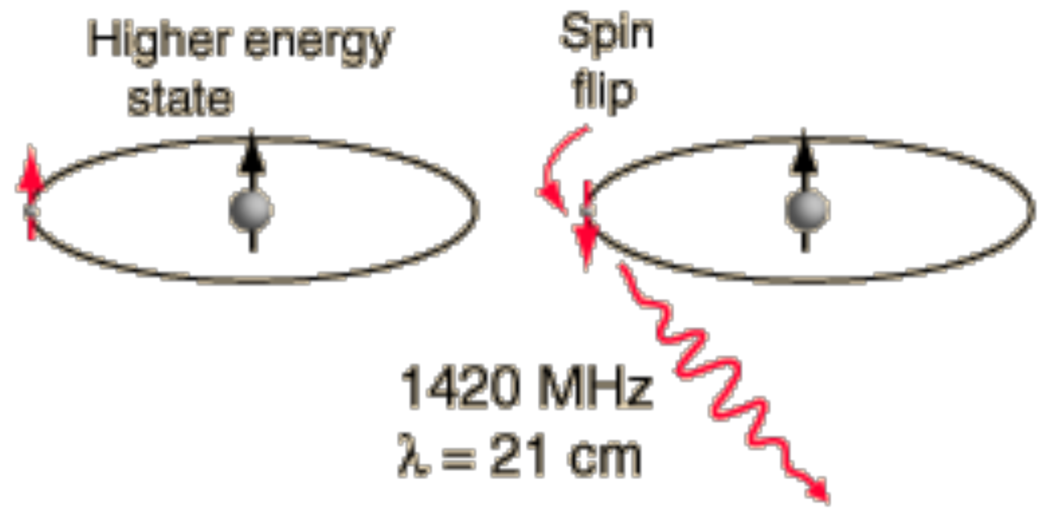
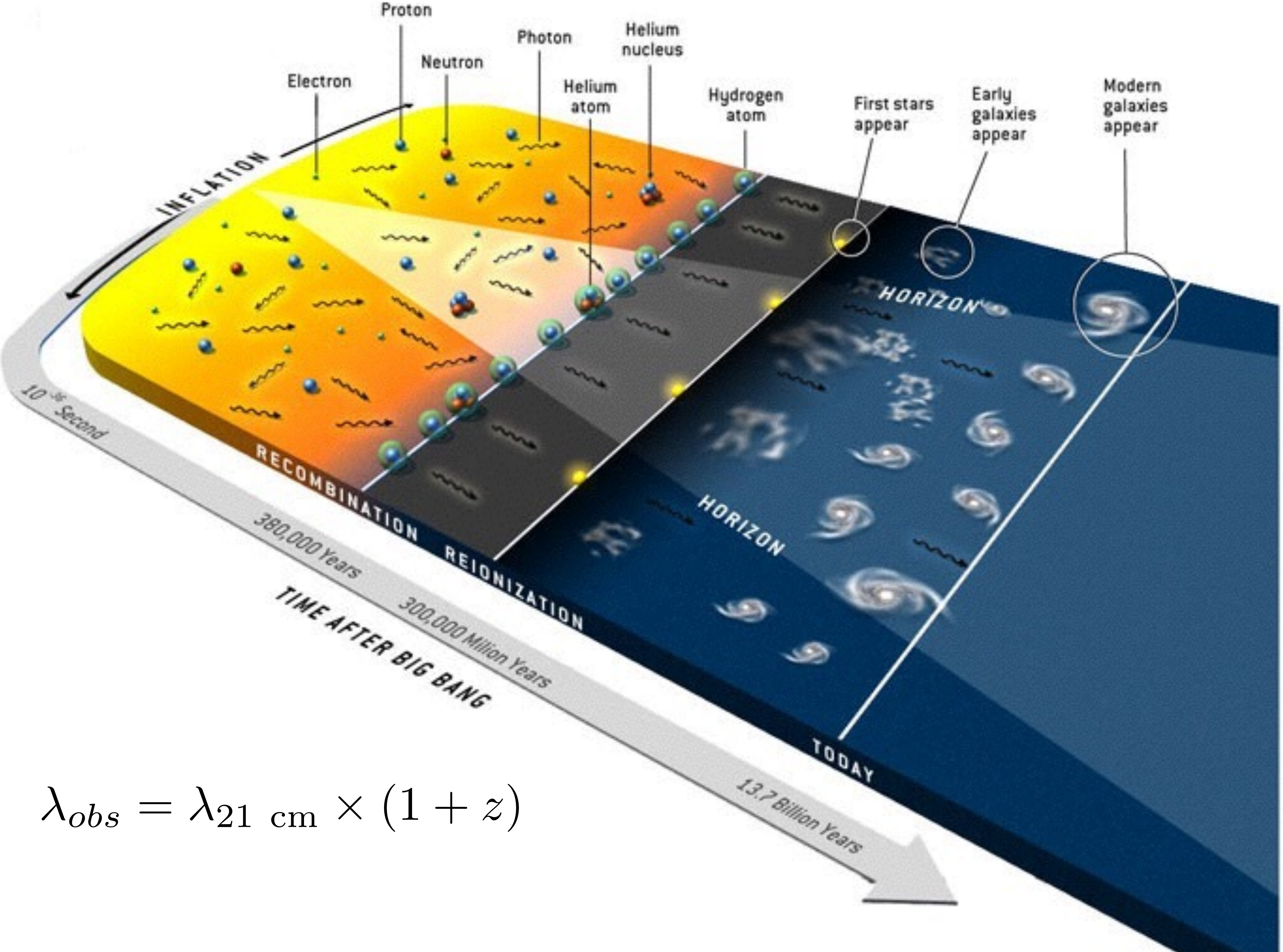
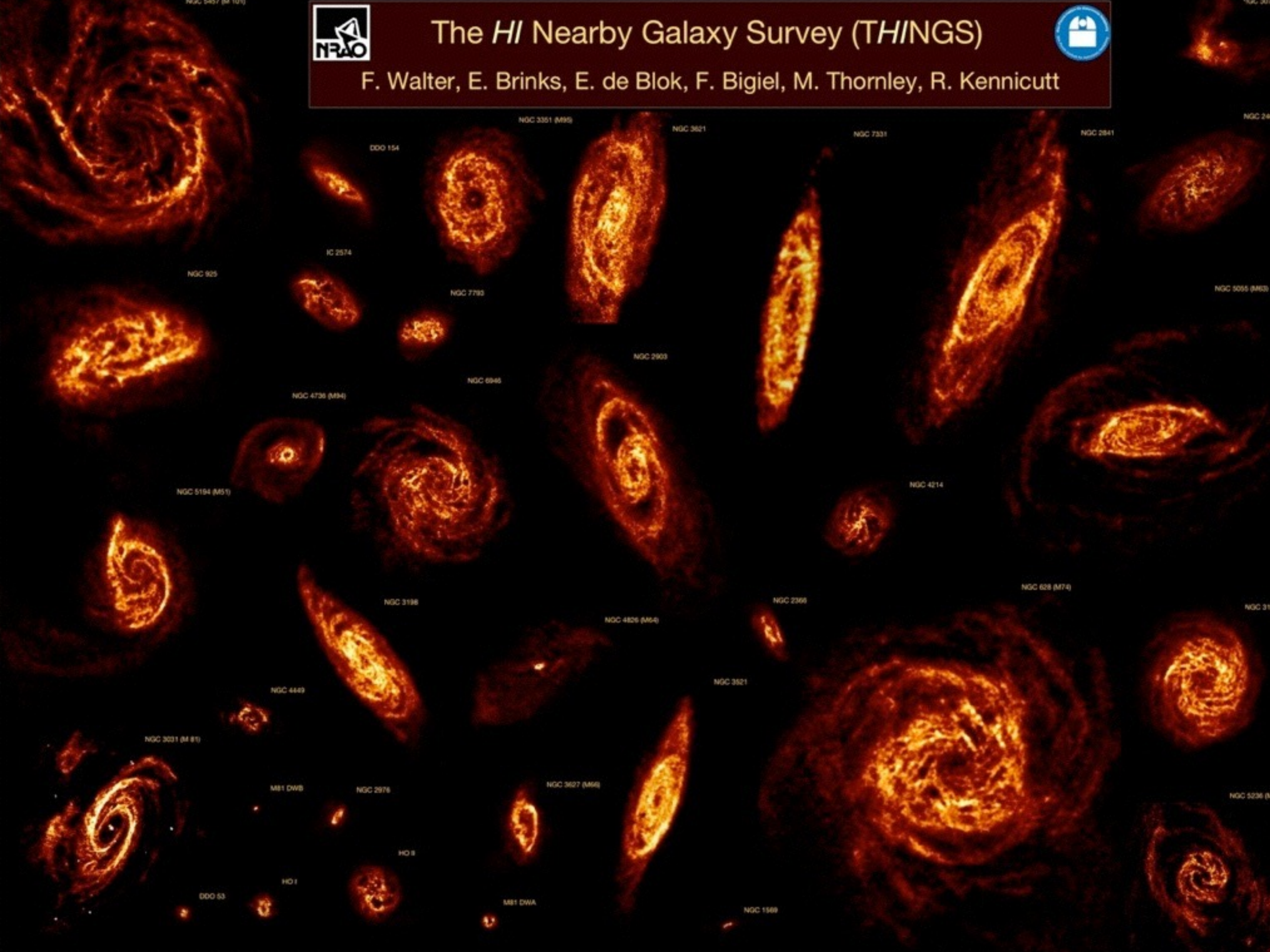


Image courtesy: Bryan Christie Design

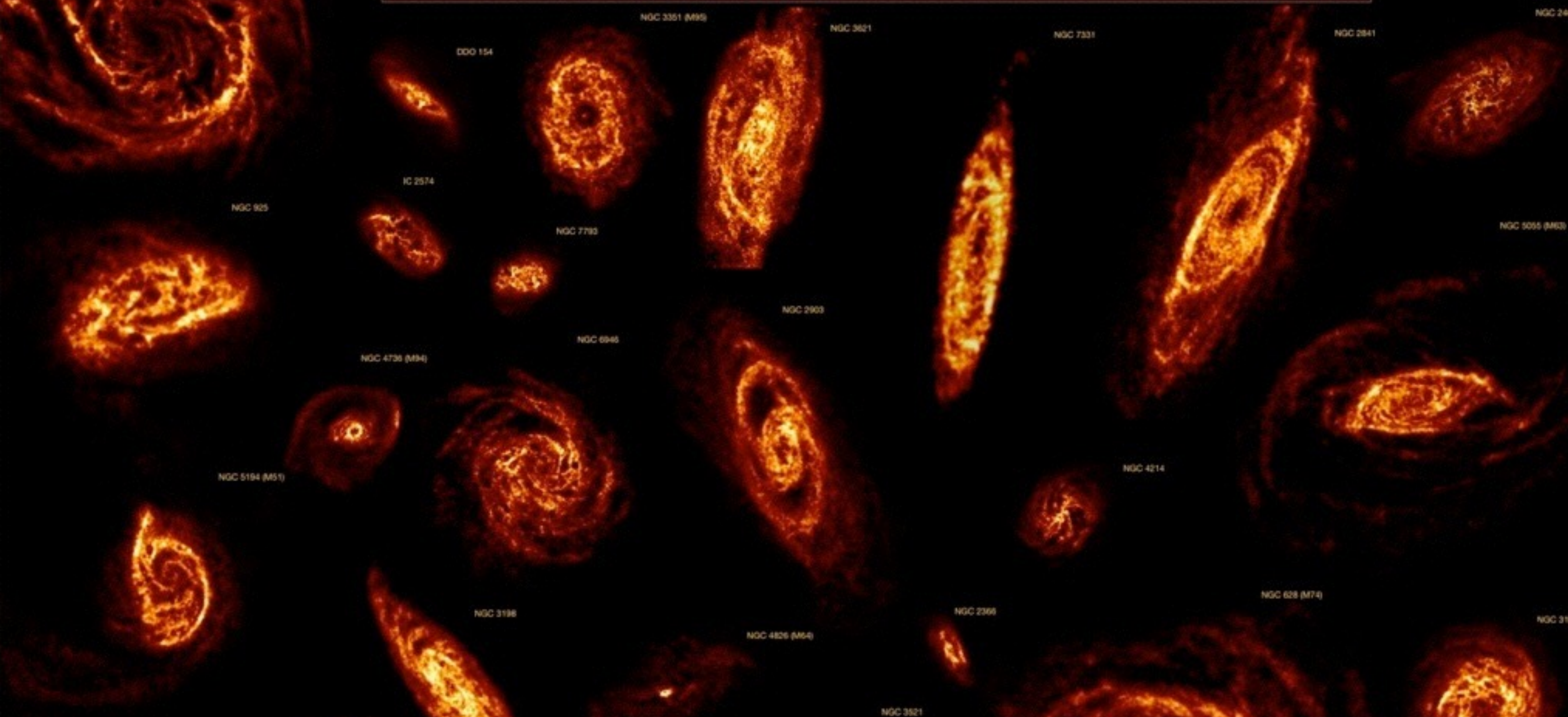


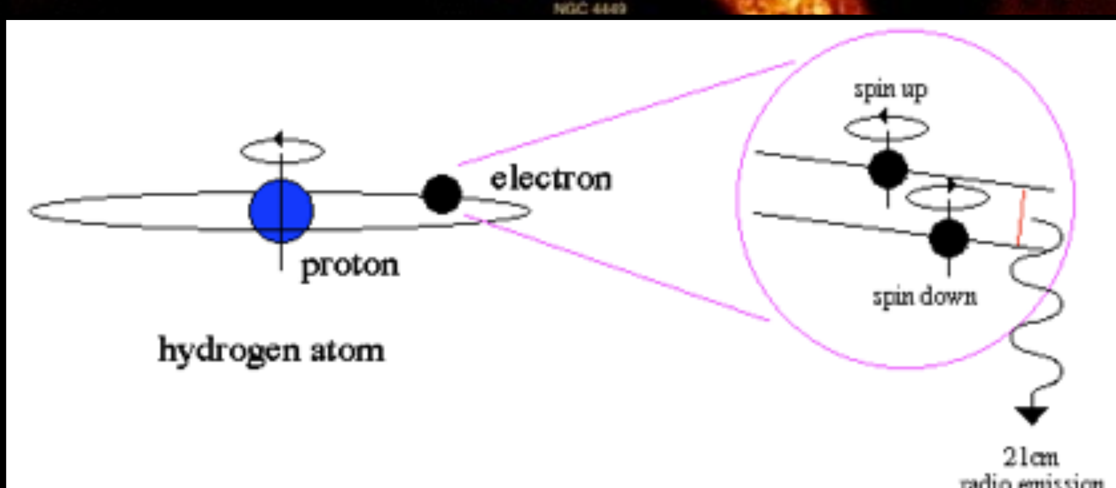
$$\lambda_{obs} = \lambda_{21\ \mathrm{cm}} \times (1 + z)$$

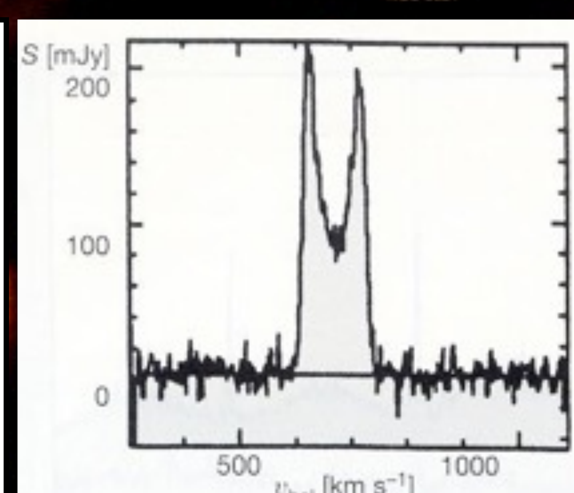

The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
DDO 154
IC 2574
NGC 925
NGC 7793
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 5055 (M63)
NGC 5194 (M51)
NGC 4214
NGC 628 (M74)
NGC 3198
NGC 2366
NGC 4826 (M64)
NGC 3521
NGC 4449
NGC 3031 (M 81)
M81 DWB
NGC 2976
NGC 3627 (M66)
HO II
HO I
DDO 53
M81 DWA
NGC 1569

The *HI* Nearby Galaxy Survey (TH*I*NGS)

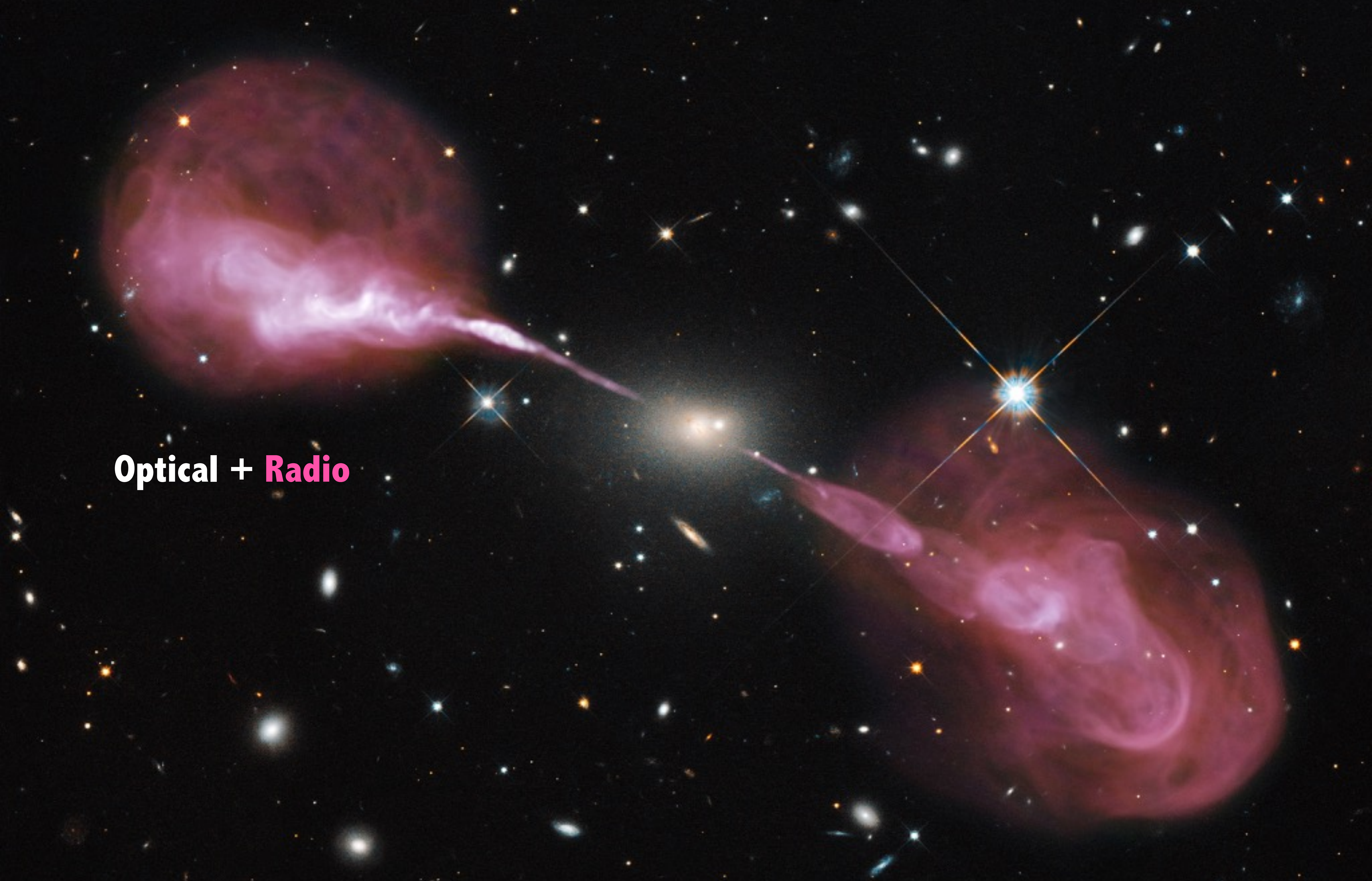
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt





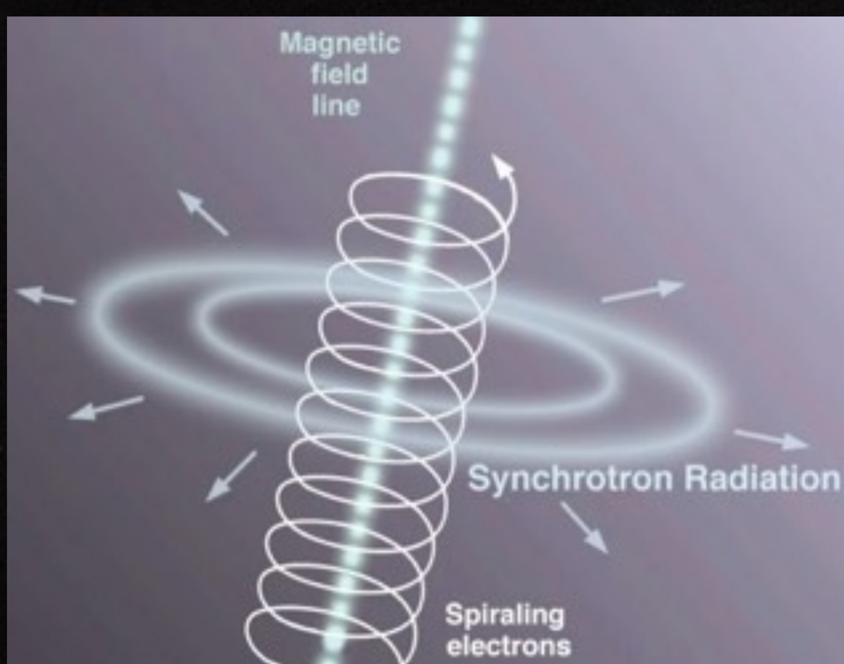


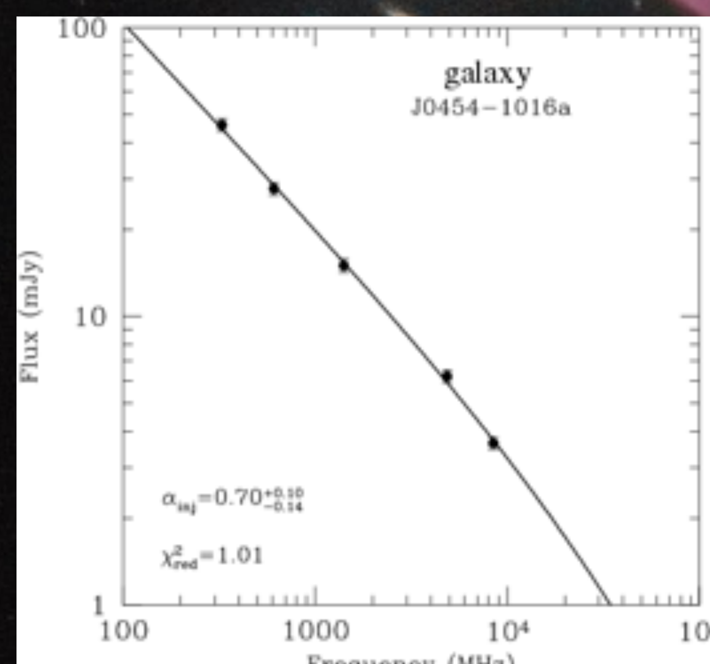
Hercules A radio galaxy



NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

Hercules A radio galaxy





NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

Preparation process to the SKA

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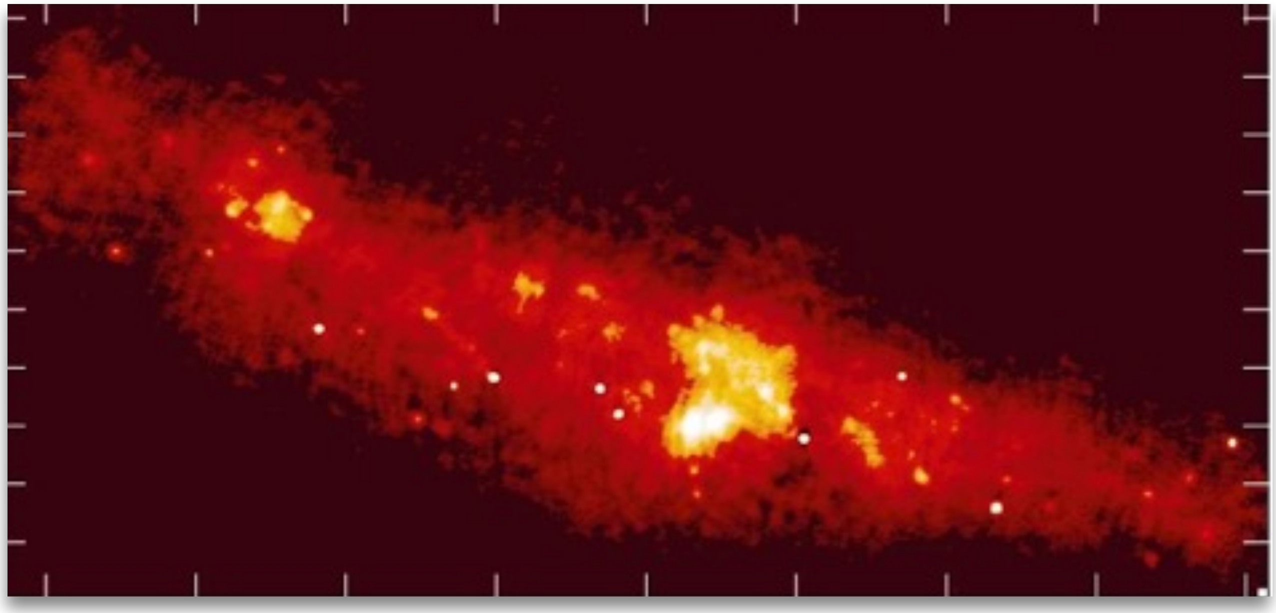
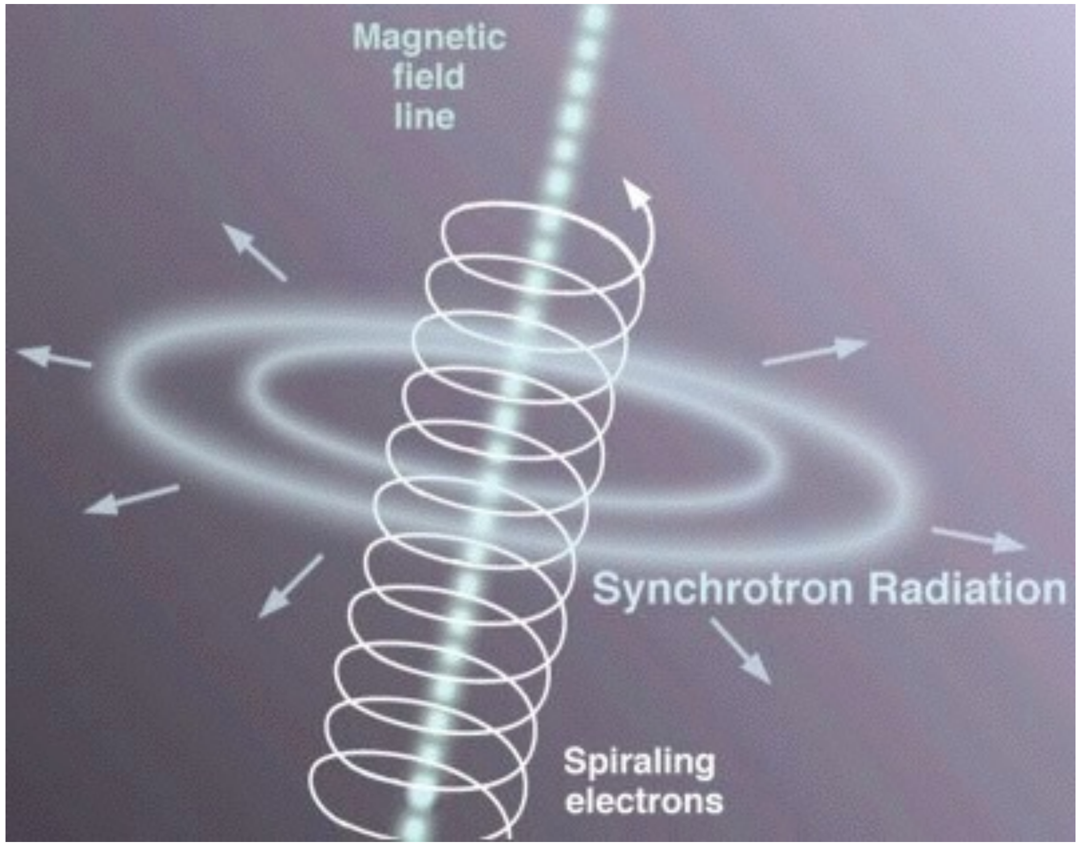
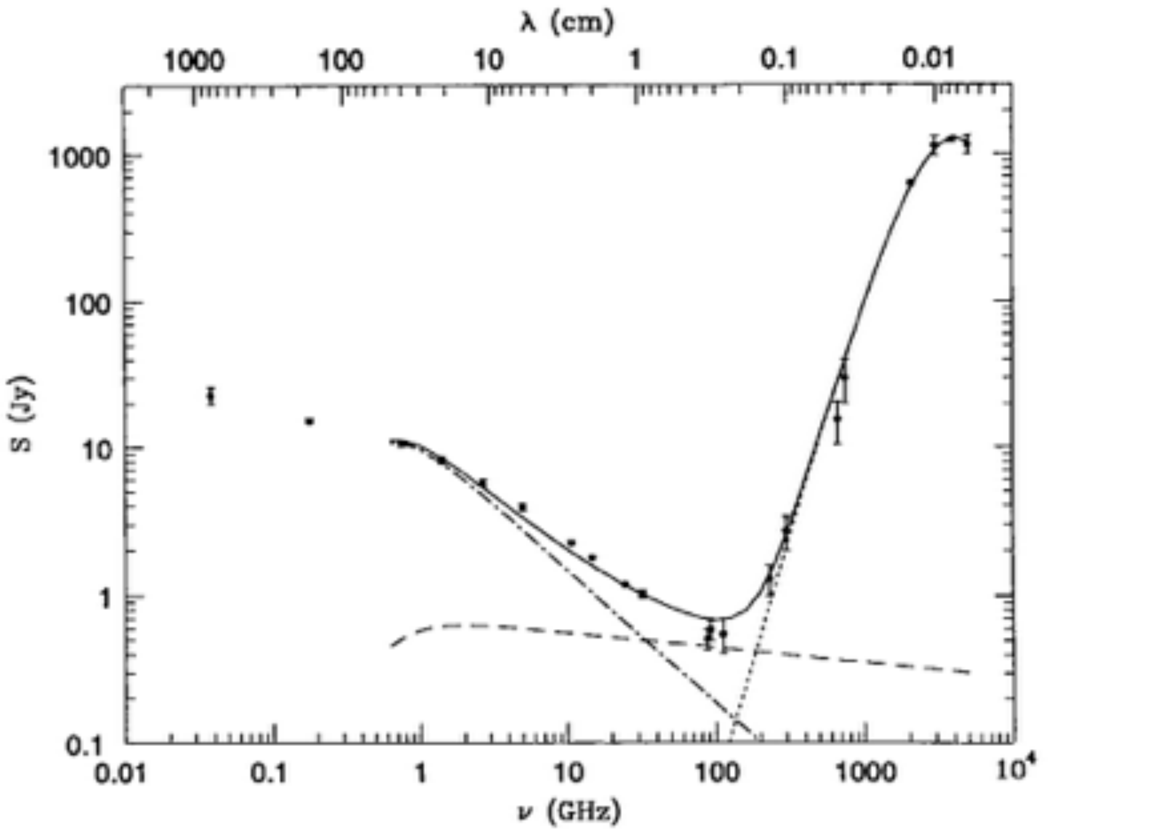
- Galaxy Evolution – HI
- **Galaxy Evolution – Continuum**
- **Cosmic Magnetism**



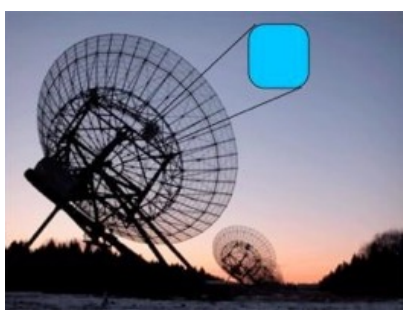




A Golden Age for Radioastronomy:
SKA Precursors and pathfinders

LOFAR
Europe
30-80 MHz +
110-240 MHz

MWA
Australia
80 - 300 MHz



APERTIF
The Netherlands
1000 - 1750 MHz

ASKAP
Australia
700 - 1800 MHz

MeerKAT
South Africa
1000 - 1750 MHz

+ JVLA

LWA

eMERLIN

eEVN

...

SKA
Australia / South Africa
~ 50 MHz - 15 GHz

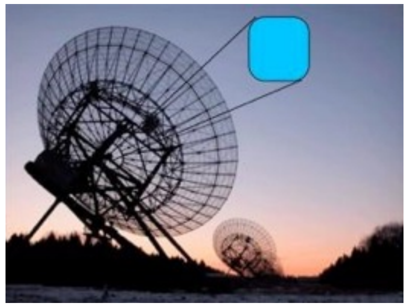
A Golden Age for Radioastronomy:
SKA Precursors and pathfinders

LOFAR
Europe
30-80 MHz +
110-240 MHz

Key Project "Surveys"
Key Project "Magnetism"

MWA
Australia
80 - 300 MHz

GLEAM
(Continuum & Polarization)



APERTIF
The Netherlands
1000 - 1750 MHz

WODAN
BEOWULF & FRIGG

ASKAP
Australia
700 - 1800 MHz

EMU
POSSUM

MeerKAT
South Africa
1000 - 1750 MHz

MIGHTEE
(Continuum & Polarization)

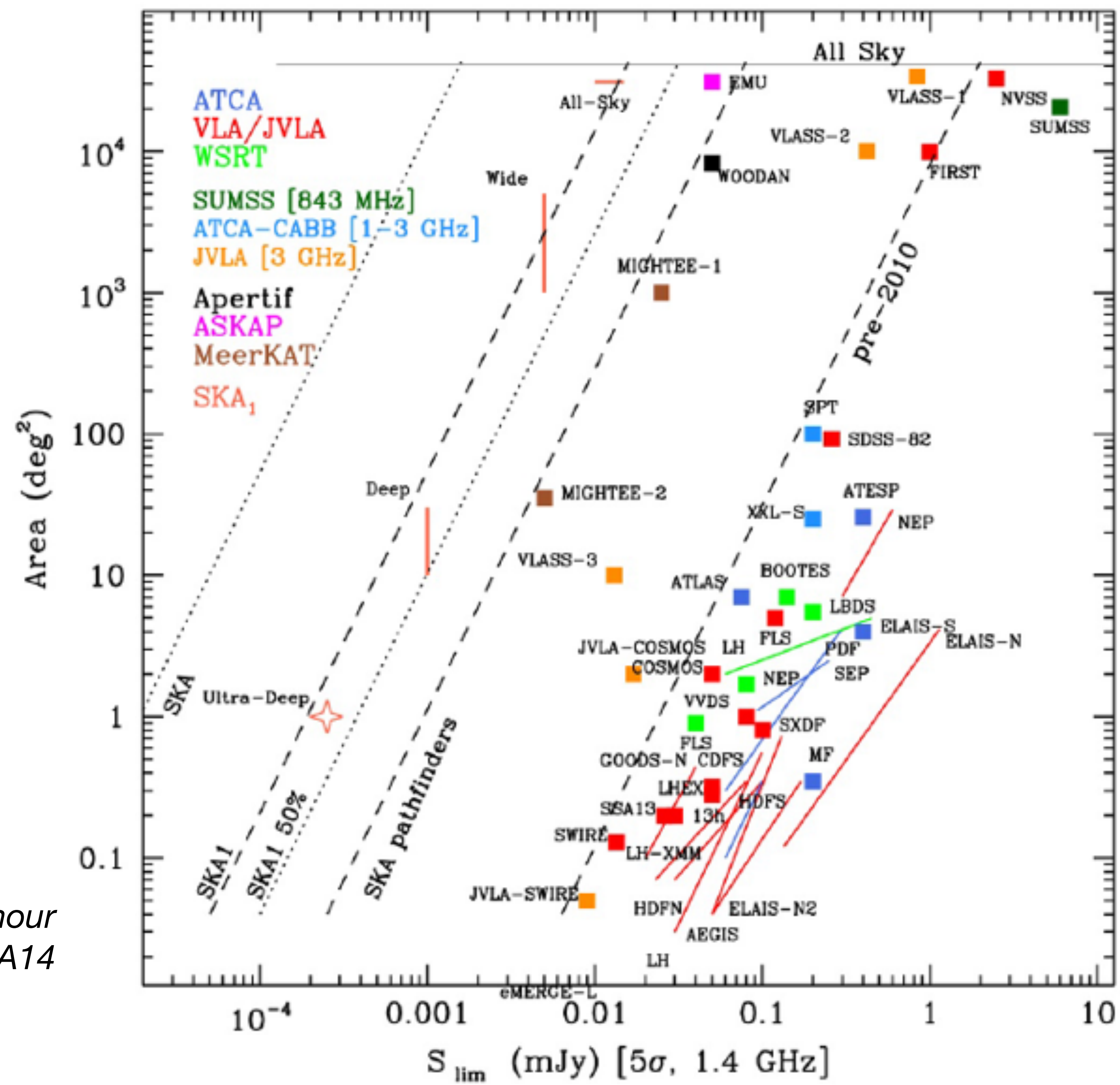
+ JVLA
LWA
eMERLIN
eEVN
...

SKA
Australia / South Africa
~ 50 MHz - 15 GHz

W.G. Continuum Surveys
W.G. Cosmic Magnetism

Summary plot for radio surveys (I)

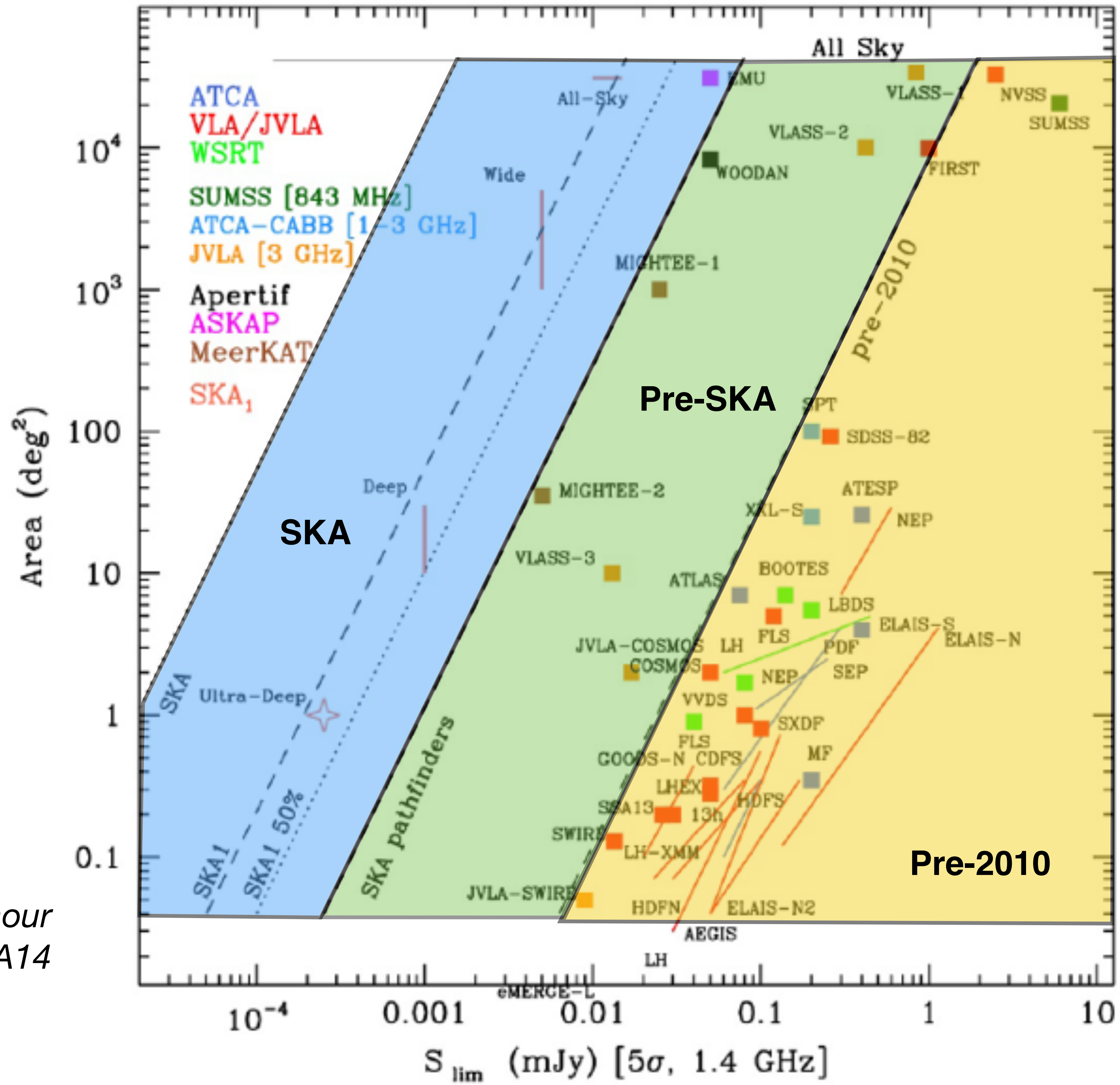
- **SFR~10 M_{Sun}/yr**: z~0.5 (Wide), z~2 (Deep), z~4 (Ultra-Deep)
- Complementary morphology & cinematic of **HI** up to z~0.8-1
- Bulk of **AGN** population down to **L~10^{22} W/Hz**, z~0.5 (Wide), z~2 (Deep), z~4 (Ultra Deep)
- **0.5'' resolution** at ~1 GHz (i.e. Euclid~0.2” & LSST~0.7")



Prandoni & Seymour AASKA14

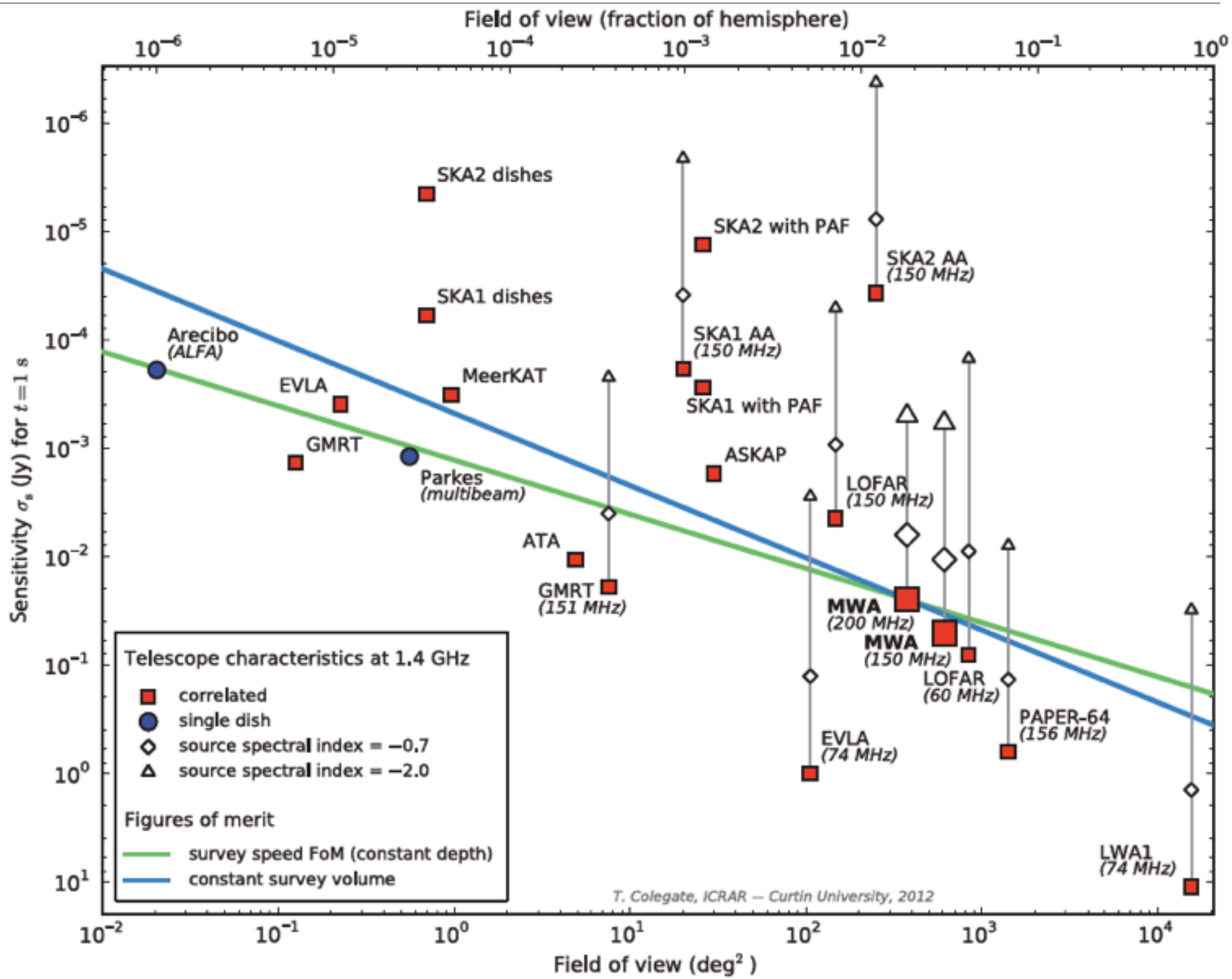
Summary plot for radio surveys (I)

- **SFR~10 M_{Sun}/yr**: z~0.5 (Wide), z~2 (Deep), z~4 (Ultra-Deep)
- Complementary morphology & cinematic of **HI** up to z~0.8-1
- Bulk of **AGN** population down to **L~10^{22} W/Hz**, z~0.5 (Wide), z~2 (Deep), z~4 (Ultra Deep)
- **0.5'' resolution** at ~1 GHz (i.e. Euclid~0.2" & LSST~0.7")



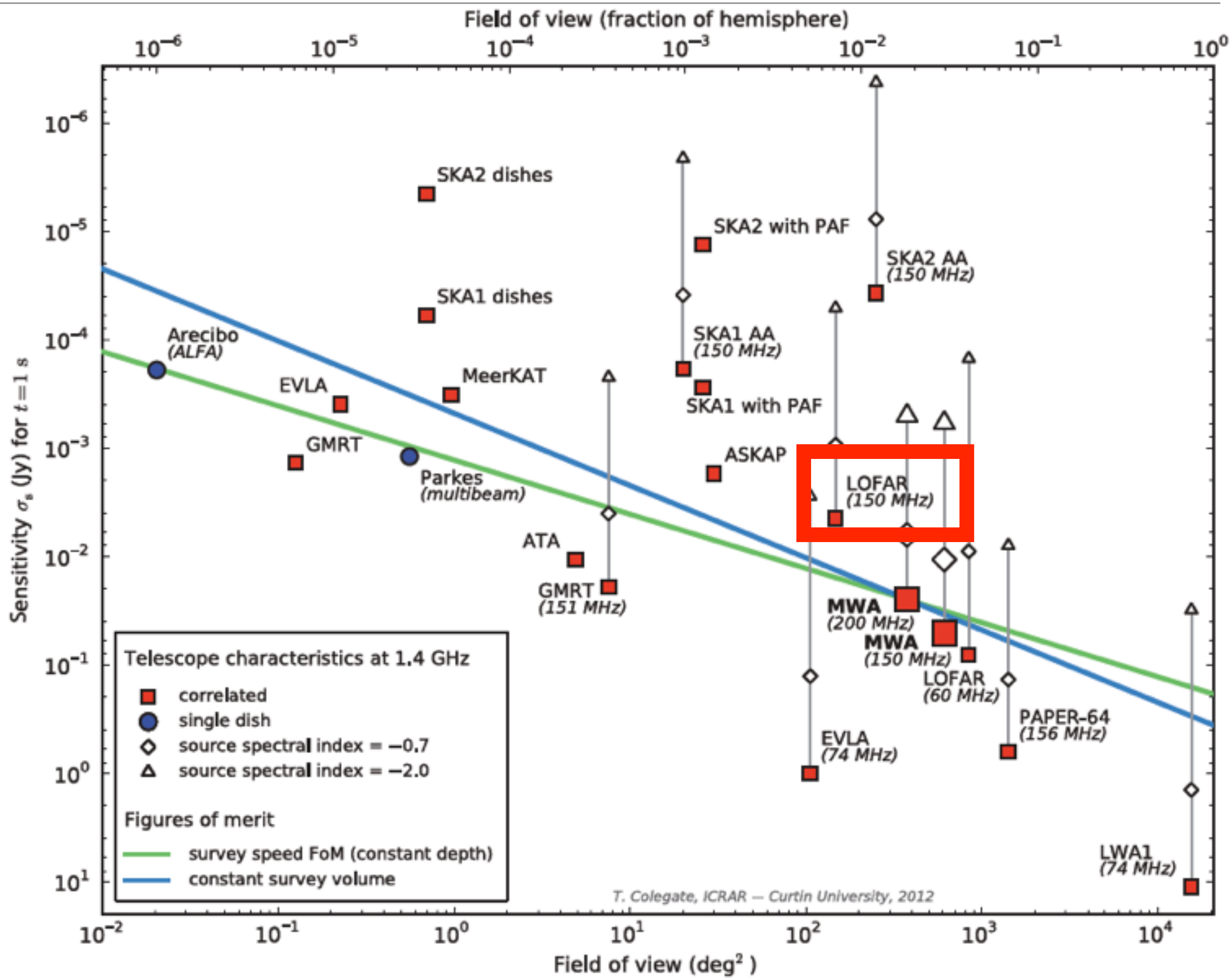
Prandoni & Seymour AASKA14

Summary plot for radio surveys (II)



Tingayy+ 13

Summary plot for radio surveys (II)

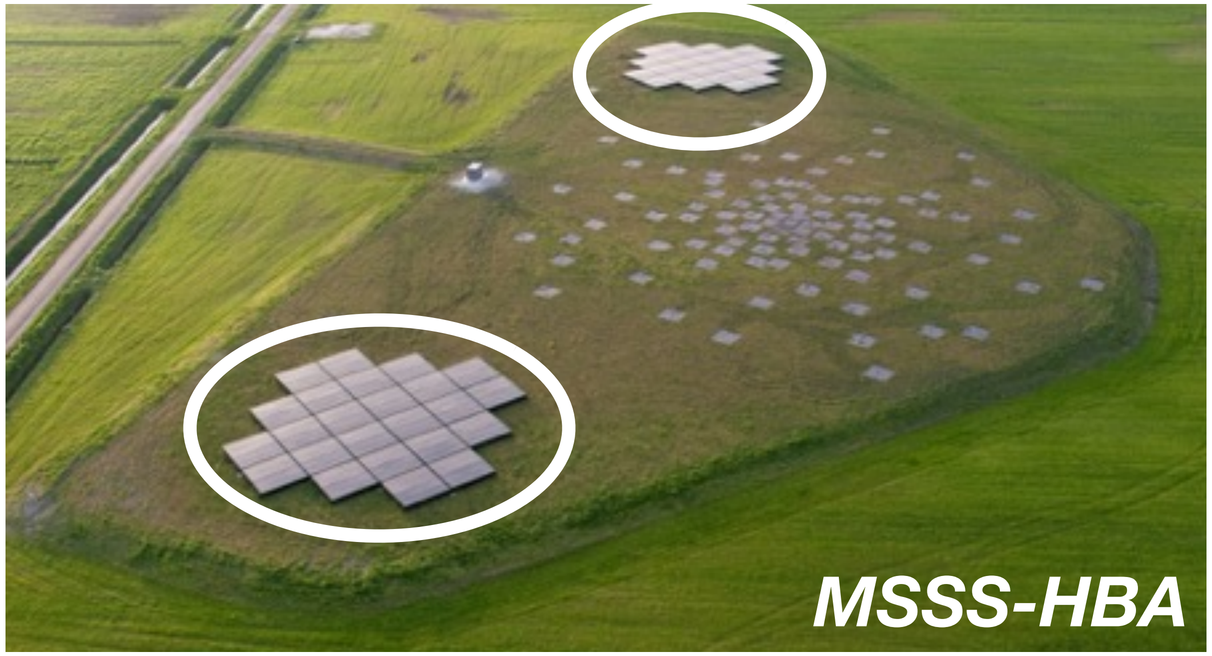


Tingayy+ 13

THE M*S*S*S TEAM

Björn Adebahr, Mike Bell, Laura Bîrzan, Annalisa Bonafede, Justin Bray, Rene Breton, Jess Broderick, Ger de Bruyn, Therese Cantwell, Dario Carbone, Patti Carroll, Yvette Cendes, Alex Clarke, Judith Croston, Soobash Daiboo, Francesco De Gasperin, Emilio Enriquez, Richard Fallows, Chiara Ferrari, Jon Gregson, Martin Hardcastle, Jeremy Harwood, Tom Hassall, Volker Heesen, Andreas Horneffer, Alexander van der Horst, Marco Iacobelli, Vibor Jelic, David Jones, Wojciech Jurusik, Georgi Kokotanekov, Giulia Macario, Poppy Martin, Carlos Martinez, John McKean, Leah Morabito, David Mulcahy, Ronald Nijboer, Błażej Nikiel-Wroczyński, Andre Offringa, Emanuela Orrú, V.N. Pandey, Gosia Pietka, Roberto Pizzo, Mamta Pommier, Peeyush Prasad, Luke Pratley, Chris Riseley, Huub Röttgering, Antonia Rowlinson, Pepe Sabater, Anna Scaife, Bart Scheers, Kati Sendlinger, Aleksandar Shulevski, Charlotte Sobey, Carlos Sotomayor, Adam Stewart, Andra Stroe, John Swinbank, Cyril Tasse, Bas van der Tol, Jonas Trüstedt, Sander ter Veen, Sjoert van Velzen, Reinout van Weeren, Wendy Williams, Michael Wise

MSSS: LOFAR's FIRST IMAGING SURVEY



- *Frequency*: 30-75 MHz
- *Resolution*: ≤100 arcsec
- *Sensitivity*: ≤15 mJy/beam
- *Area*: 20,000 square degrees
- *Simultaneous beams*: 5 (~10º)

Number of Fields: 660

- *Frequency*: 115-180 MHz
- *Resolution*: ≤120 arcsec
- *Sensitivity*: ≤5 mJy/beam
- *Area*: 20,000 square degrees
- *Simultaneous beams*: 6 (~4º)

Number of Fields: 3616

MSSS:
LOFAR's first imaging survey

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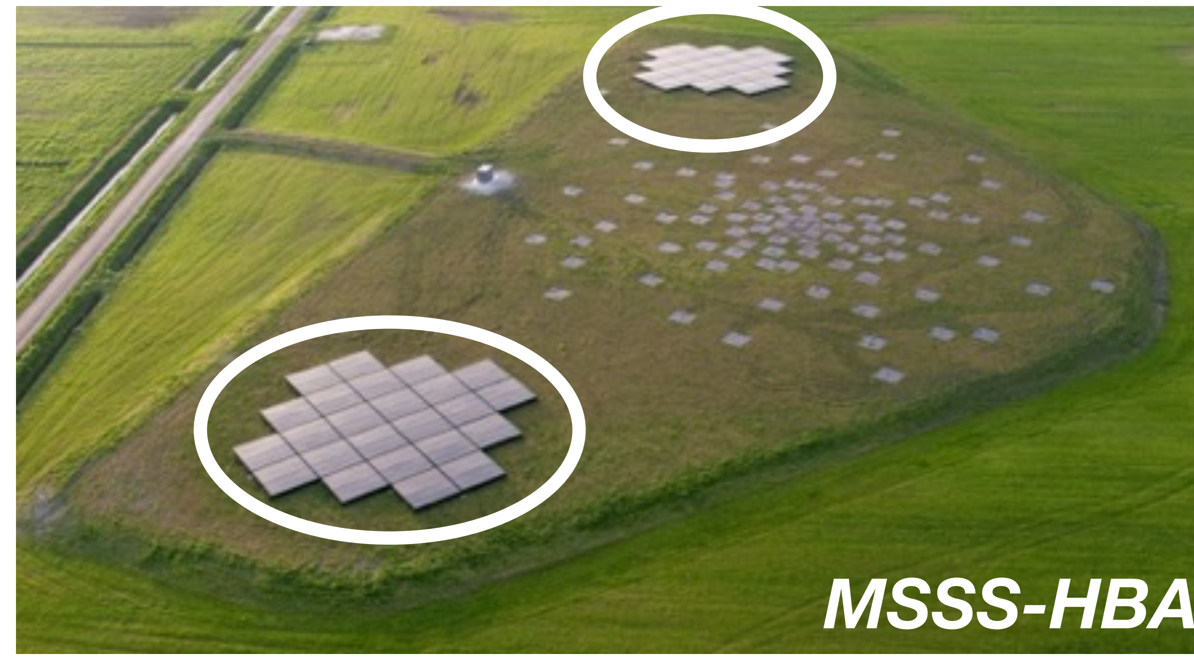

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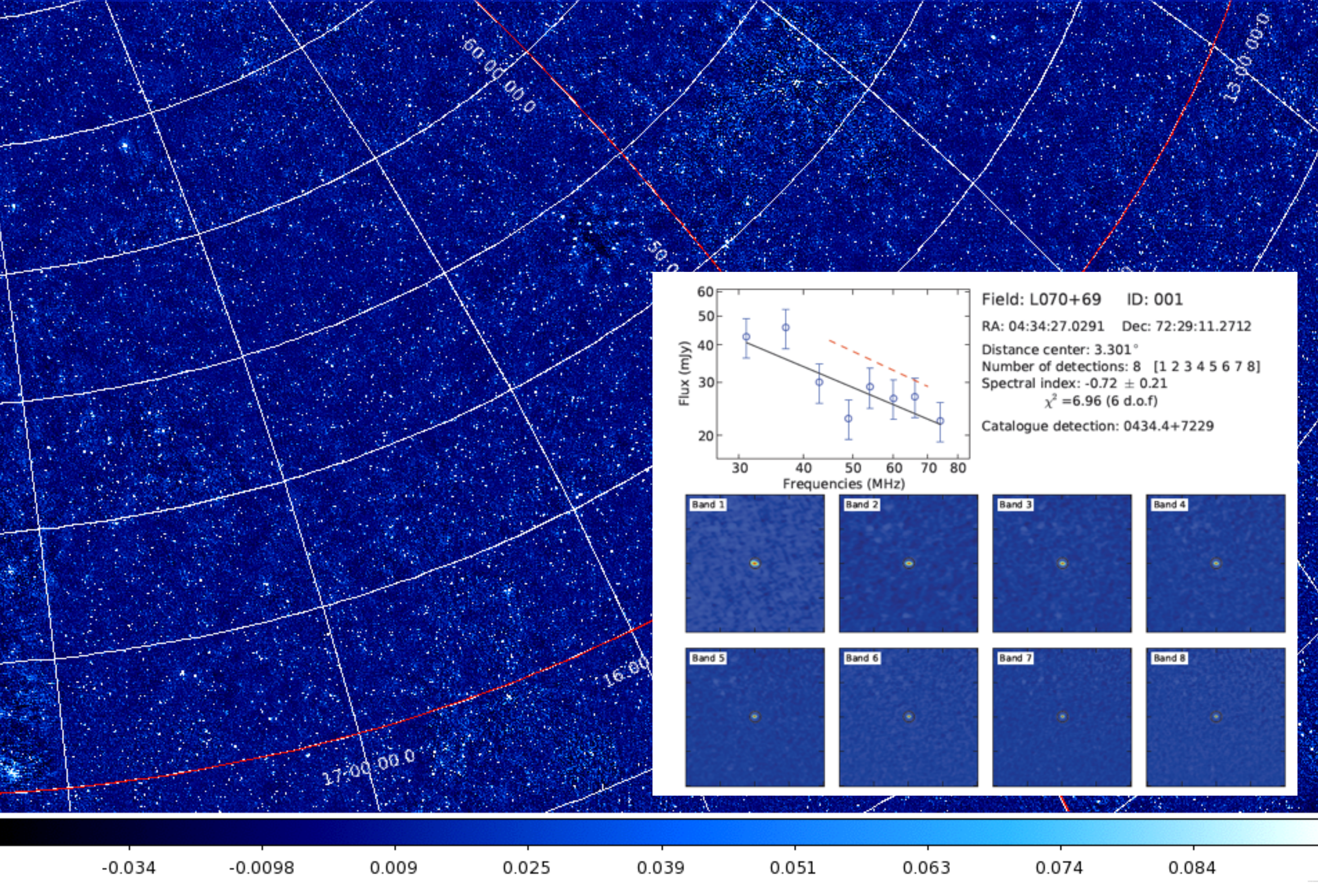
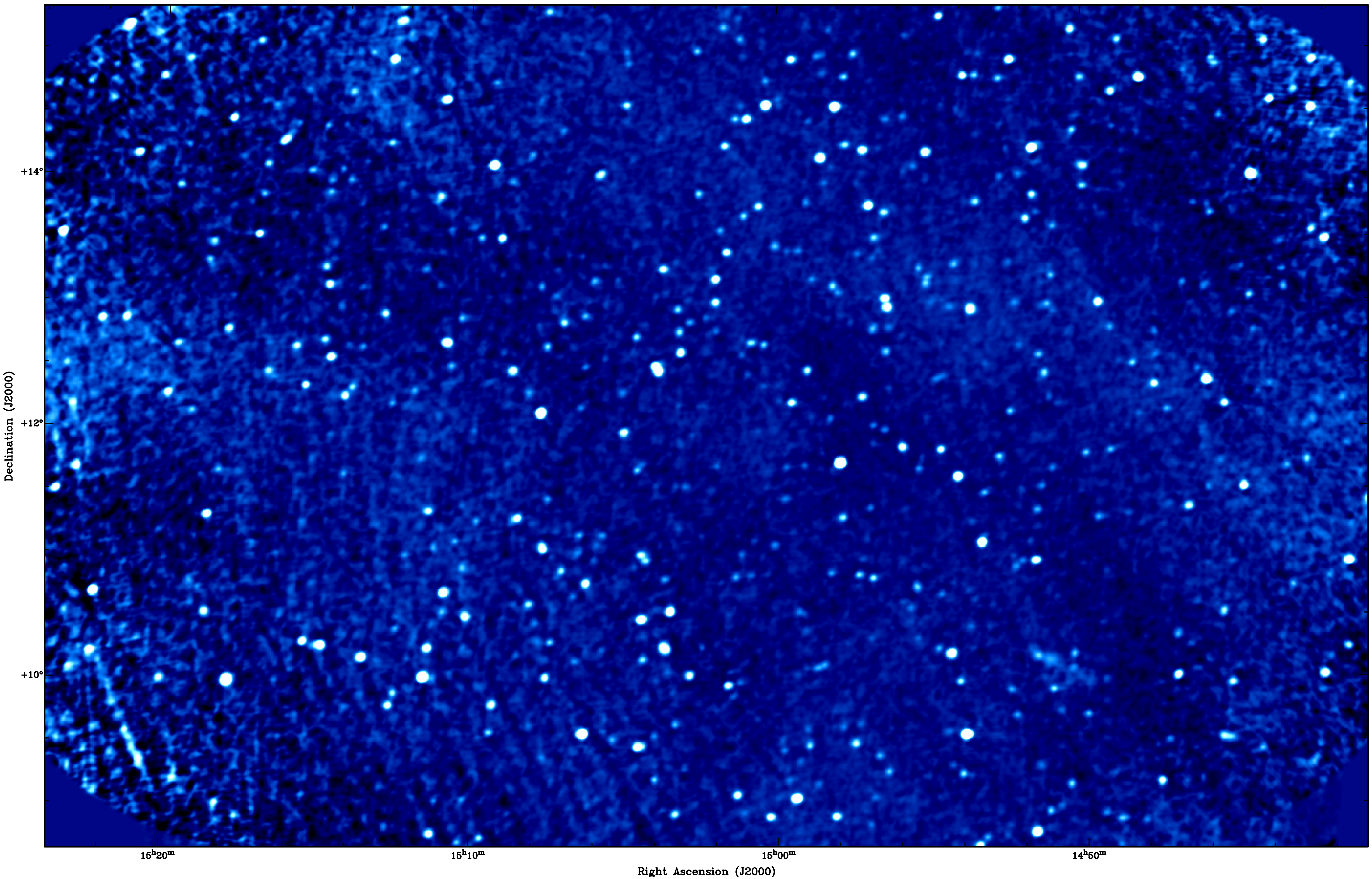
***Goals:** obtain broadband sky model & shakedown LOFAR operations*

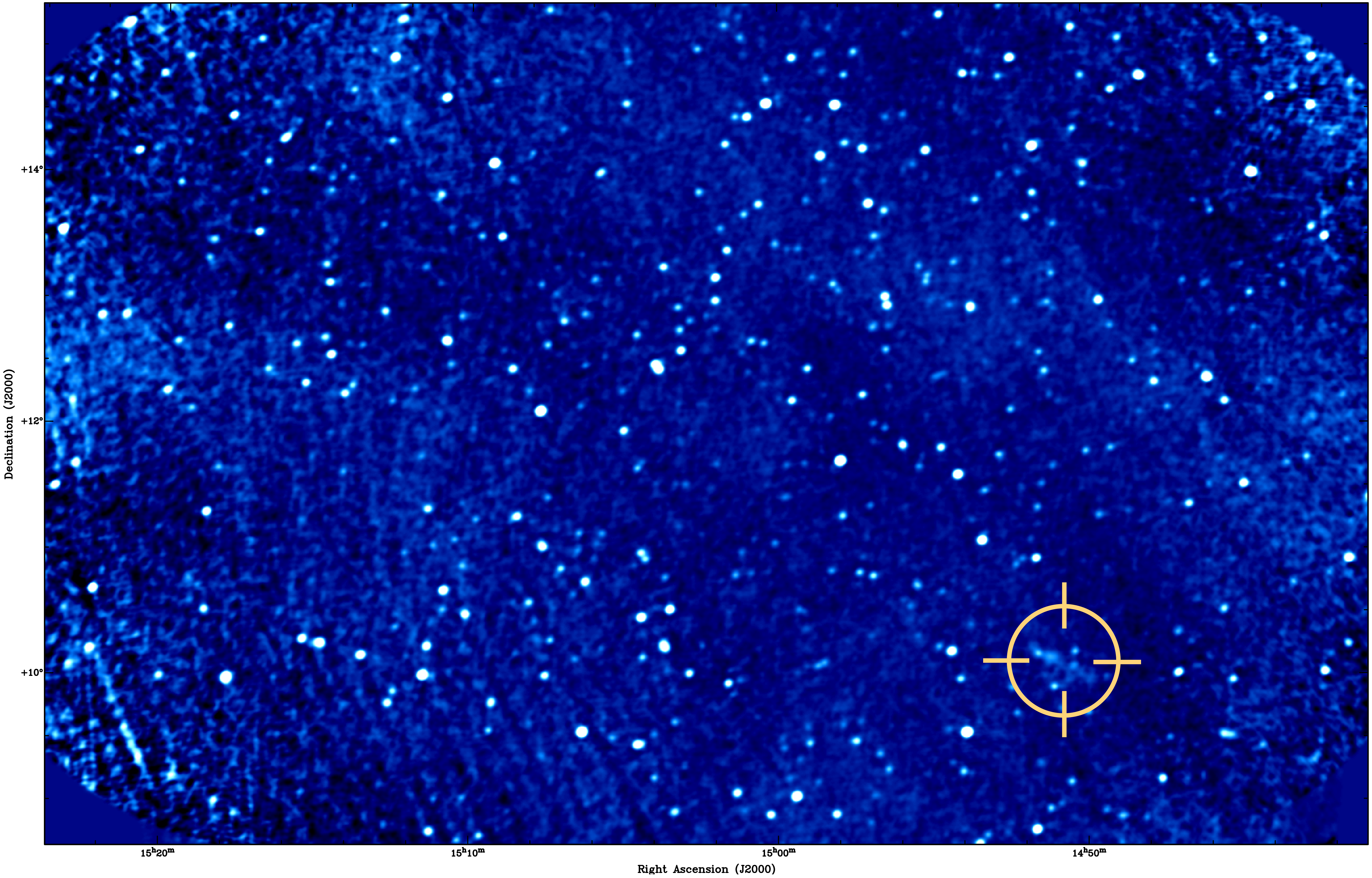
MSSS expects to catalog 150,000 - 200,000 sources

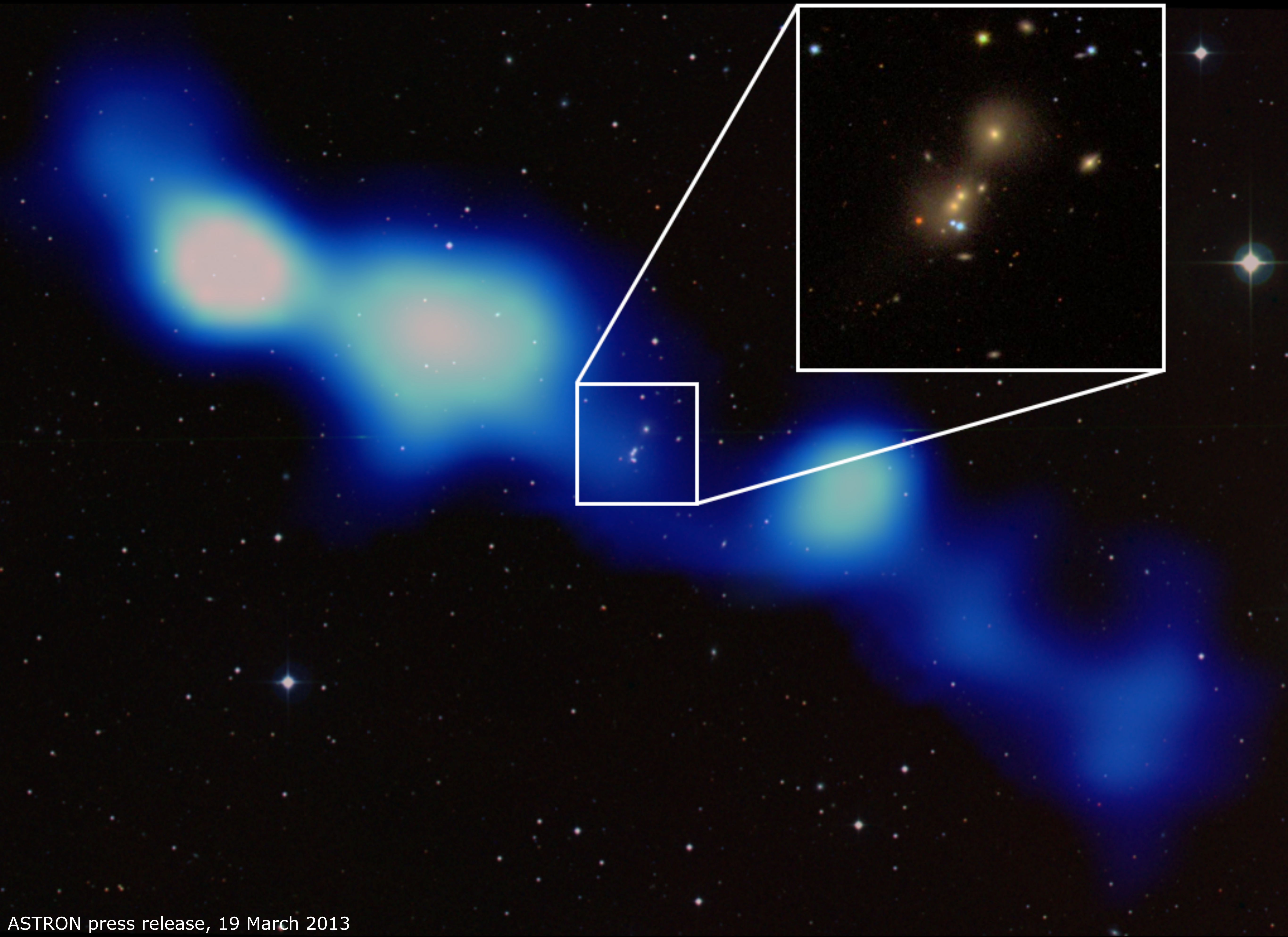


EARLY MSSS-HBA MOSAIC (1)

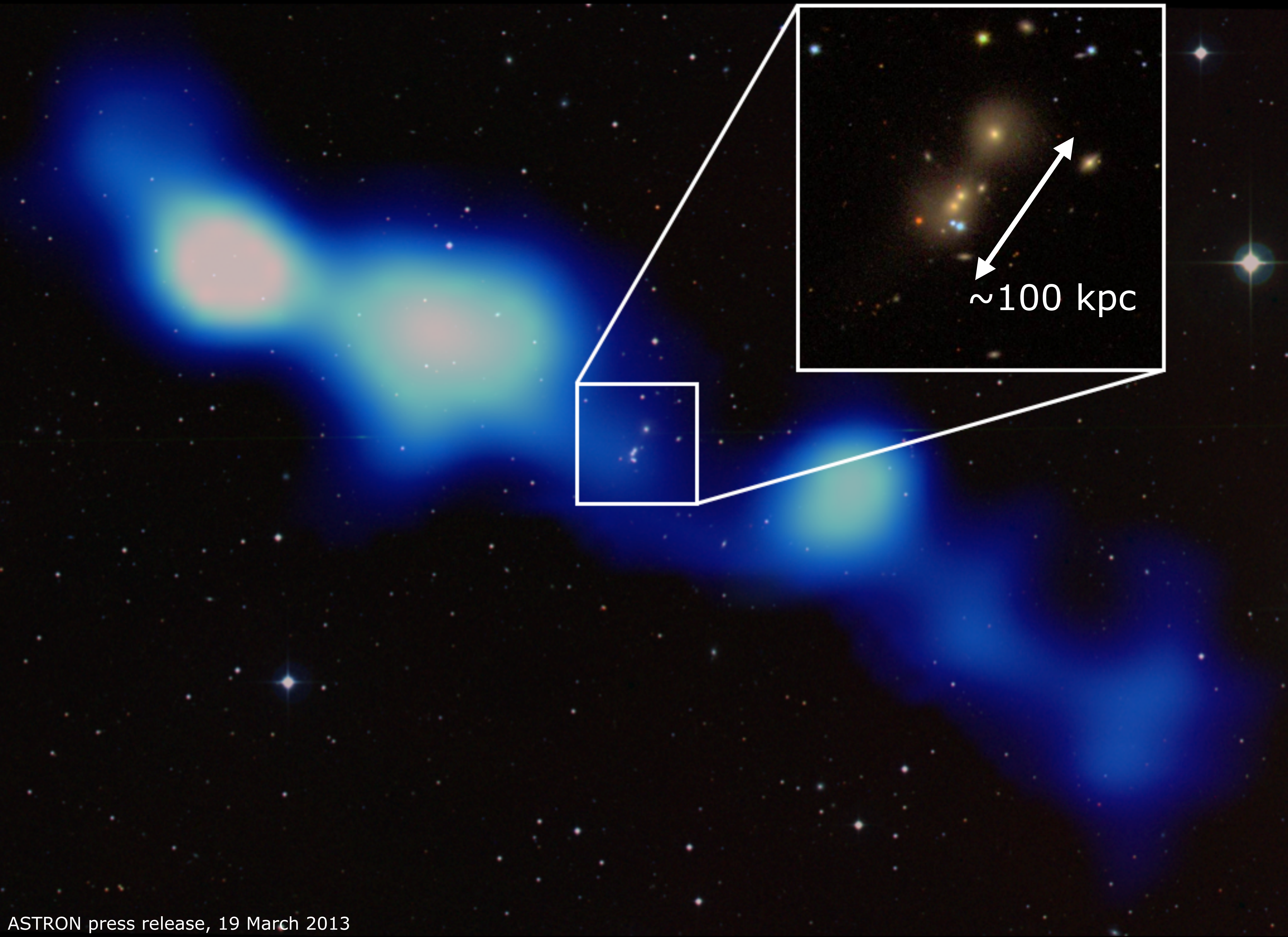


EARLY MSSS-HBA MOSAIC (1)

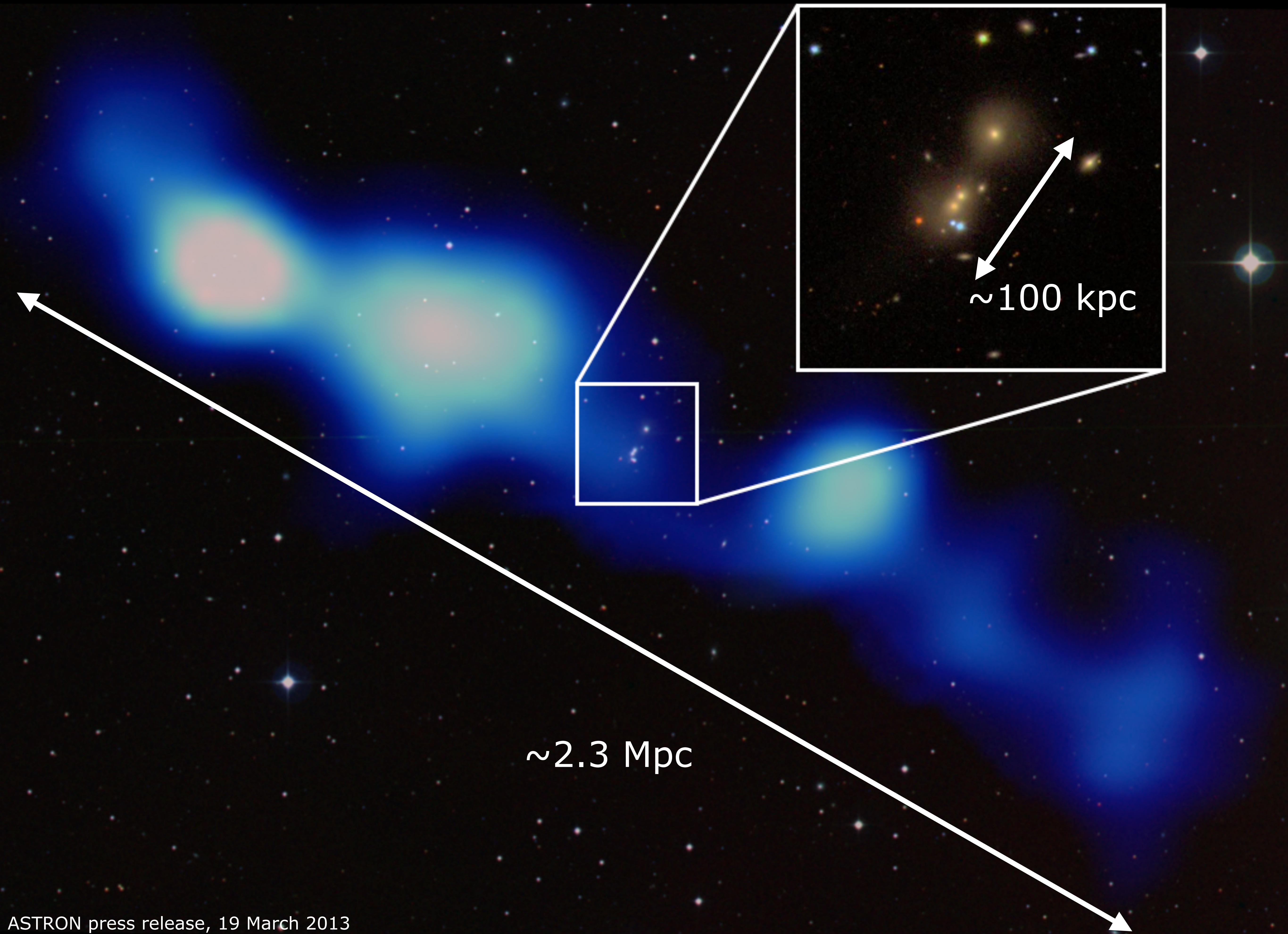




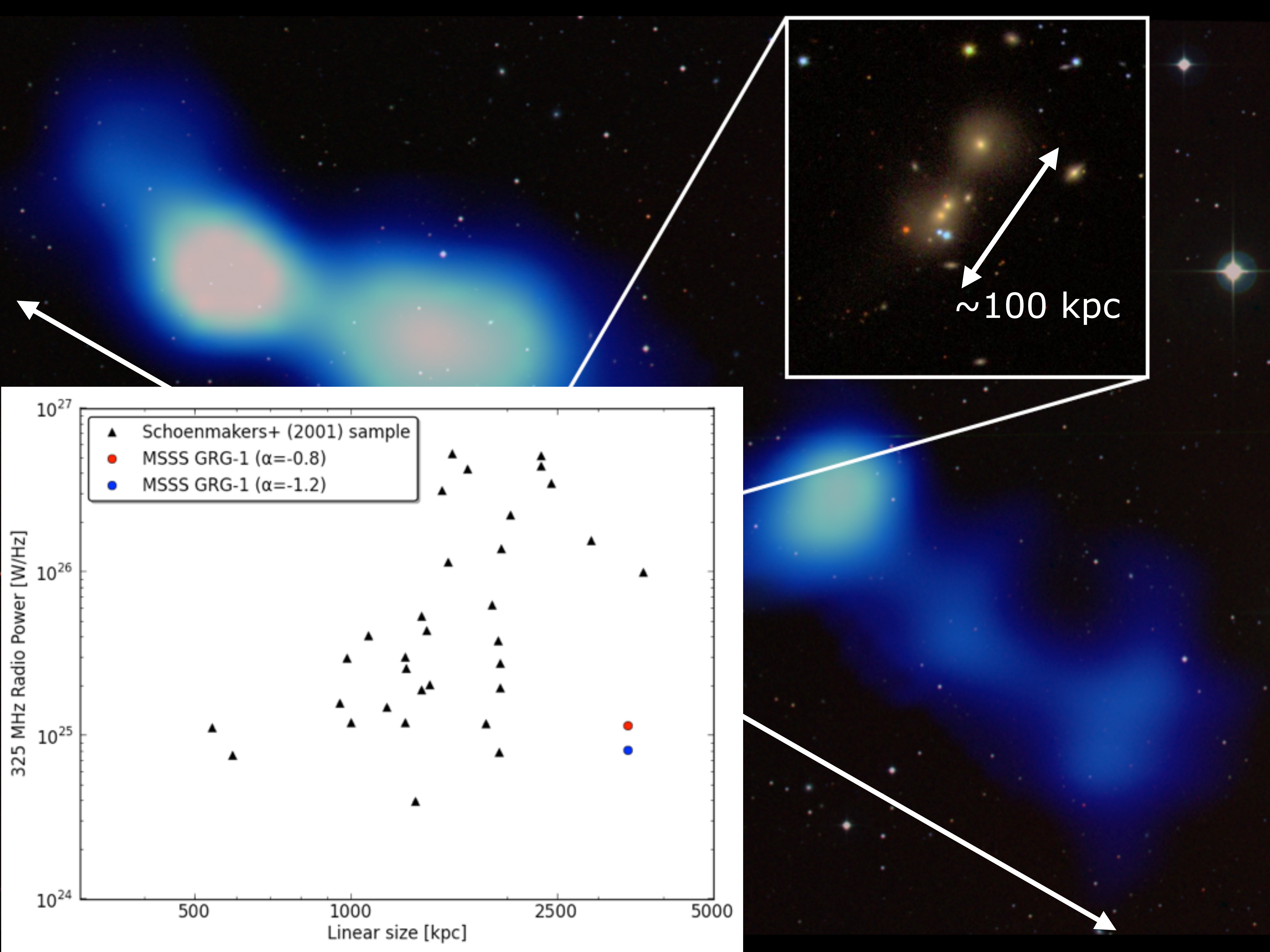
ASTRON press release, 19 March 2013



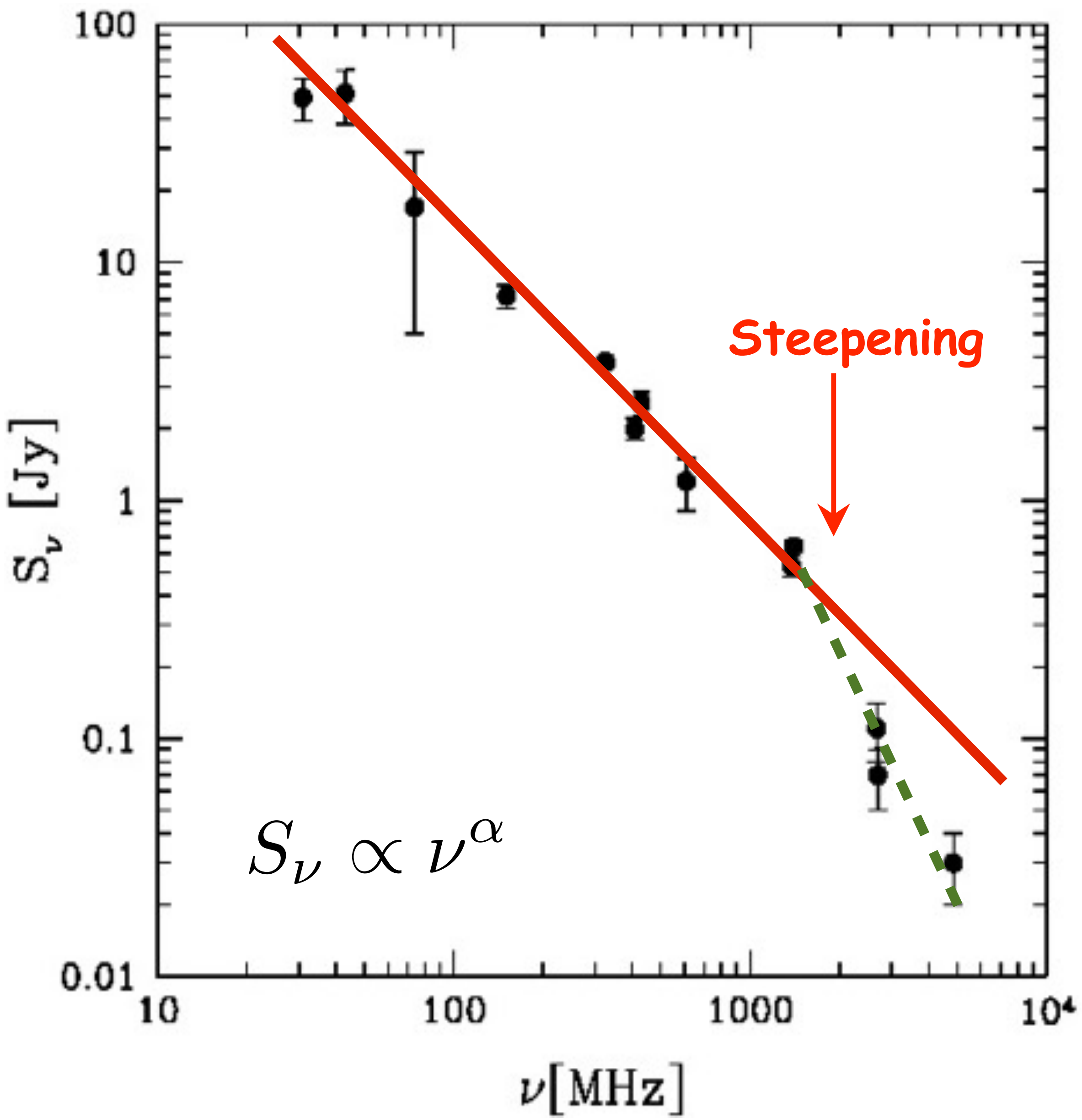
ASTRON press release, 19 March 2013



ASTRON press release, 19 March 2013


~100 kpc
Schoenmakers+ (2001) sample
MSSS GRG-1 (α=-0.8)
MSSS GRG-1 (α=-1.2)
325 MHz Radio Power [W/Hz]
Linear size [kpc]
10^{27}
10^{26}
10^{25}
10^{24}
500
1000
2500
5000

Importance of low frequency observations



Peak frequency of synchrotron emission :

$$\nu \;=\; 4.2\,\gamma^2 \left(\frac{\mathrm{B}}{1\ \mu\mathrm{G}}\right)\ (1\ +\ z)^{-1}\ \mathrm{Hz}$$

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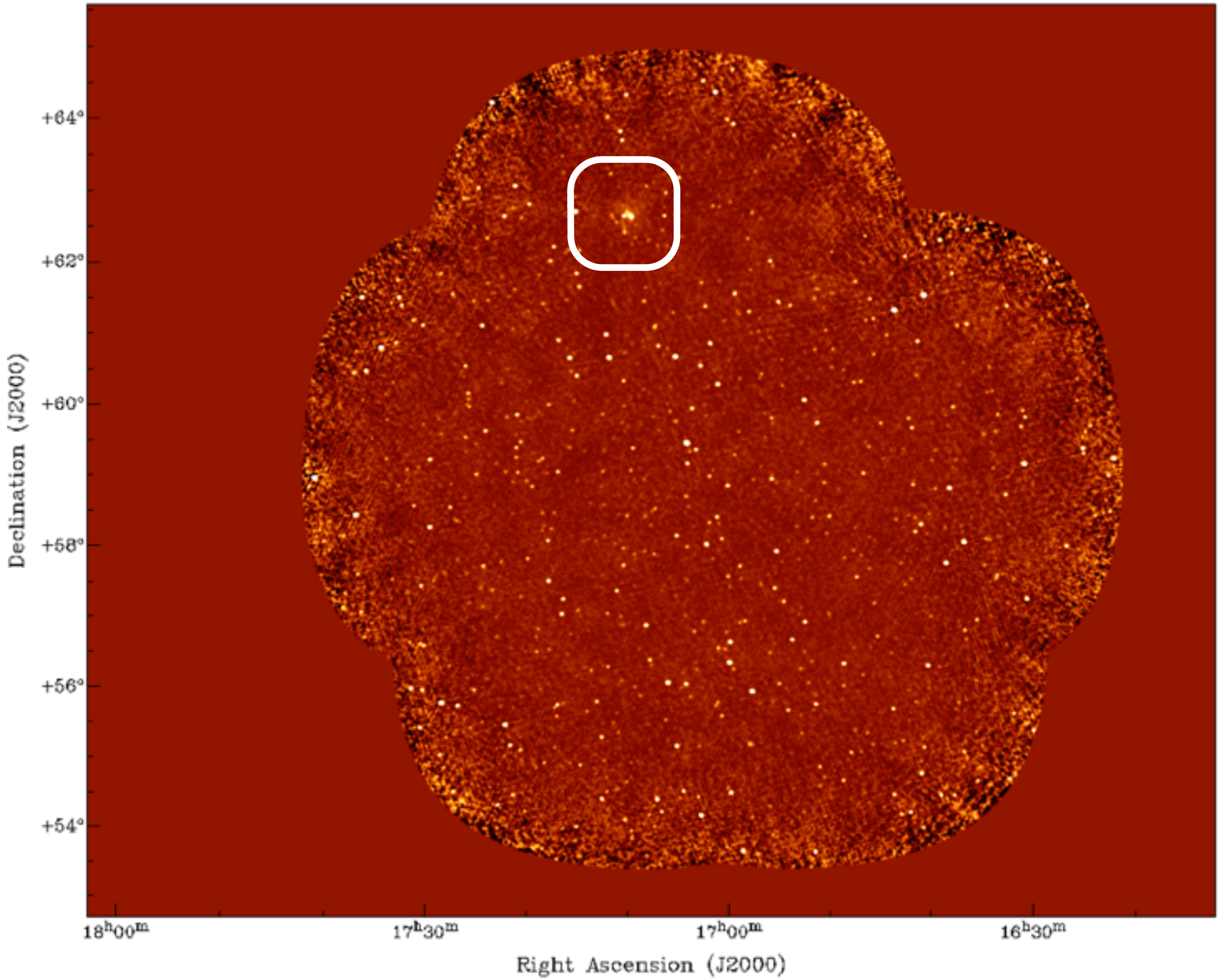
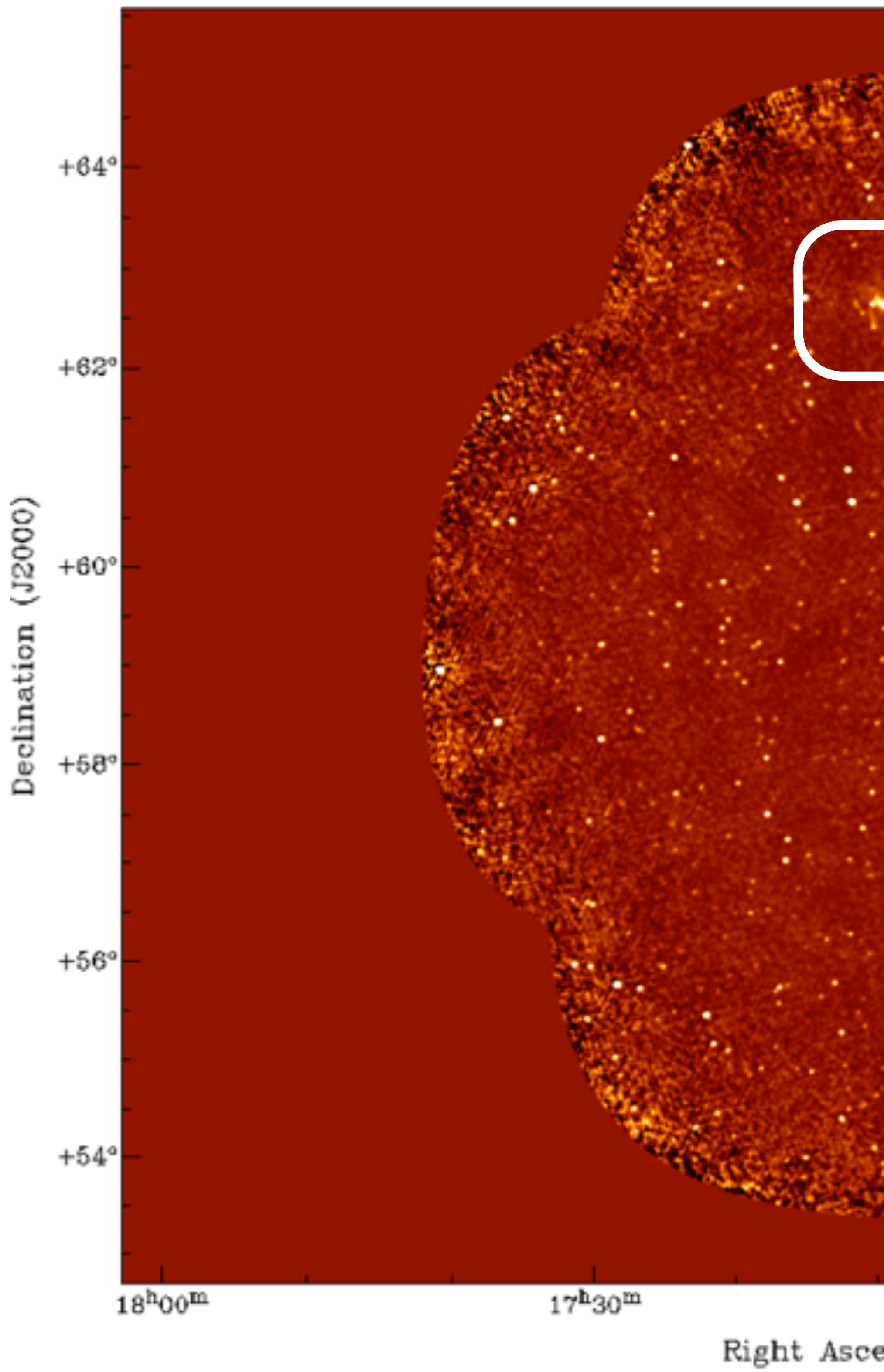
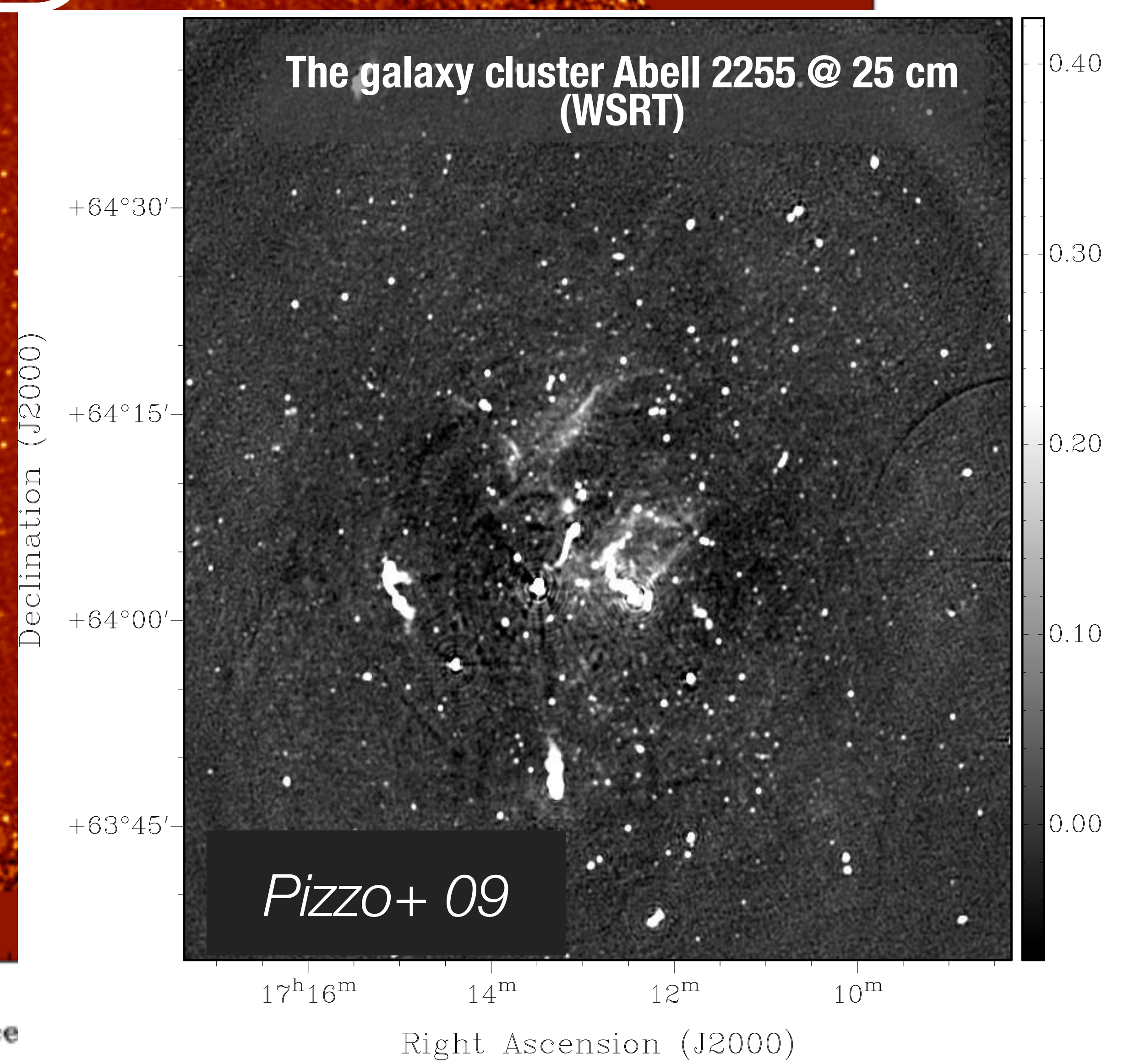
EARLY MSSS-HBA MOSAIC (2)



EARLY MSSS-HBA MOSAIC (2)

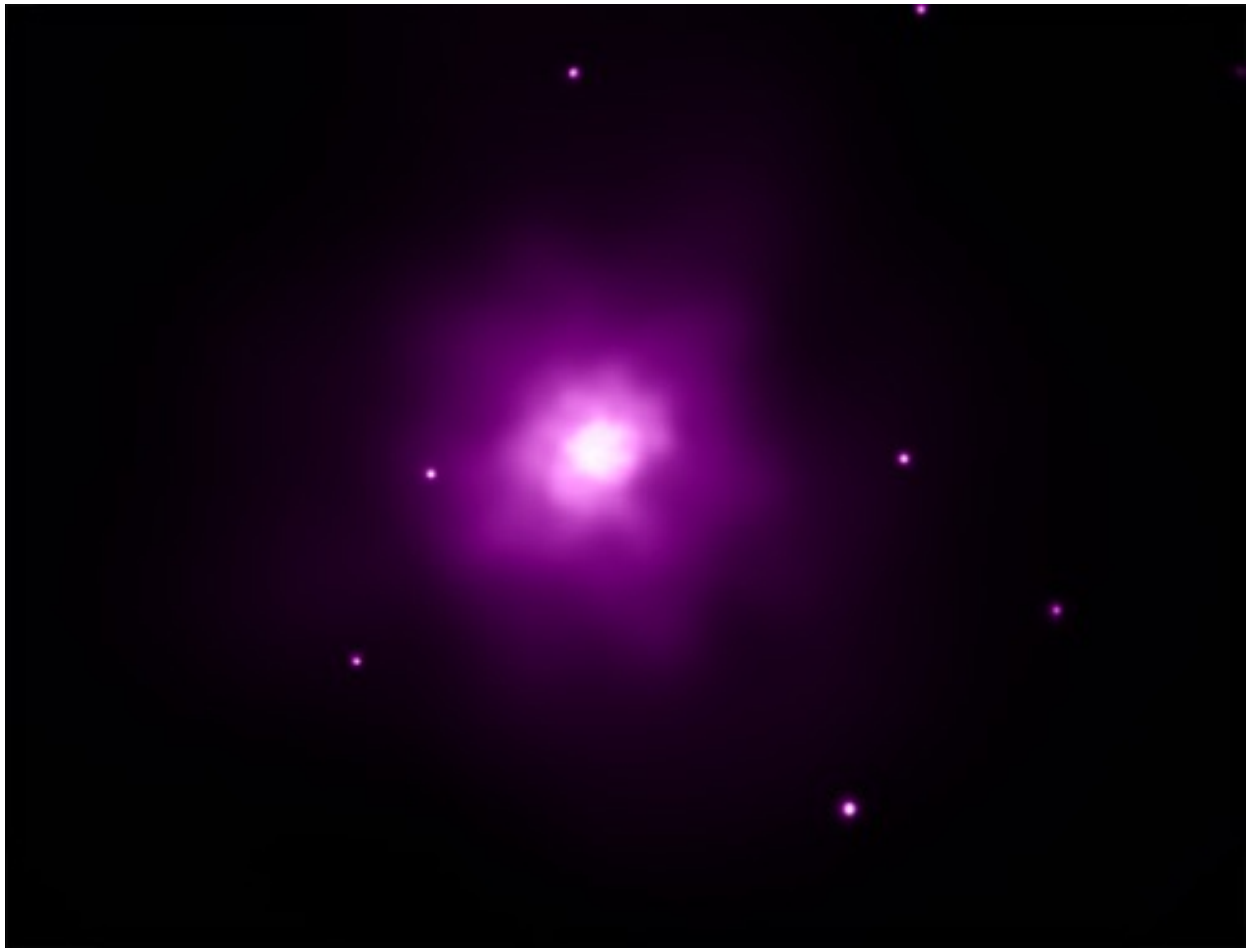




Clusters of galaxies

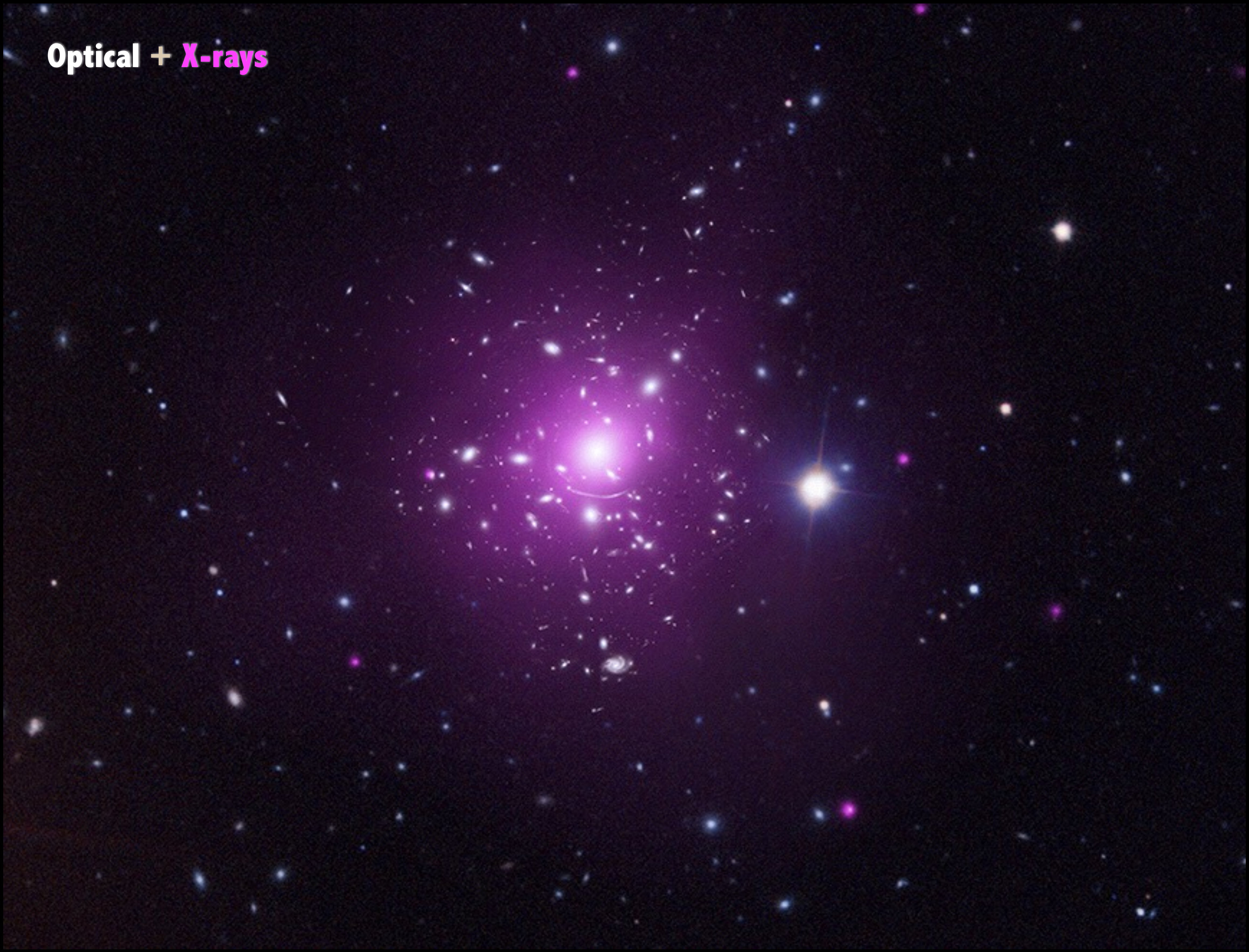
Optical: NASA/STScI, ESO/VLT, SDSS

Clusters of galaxies

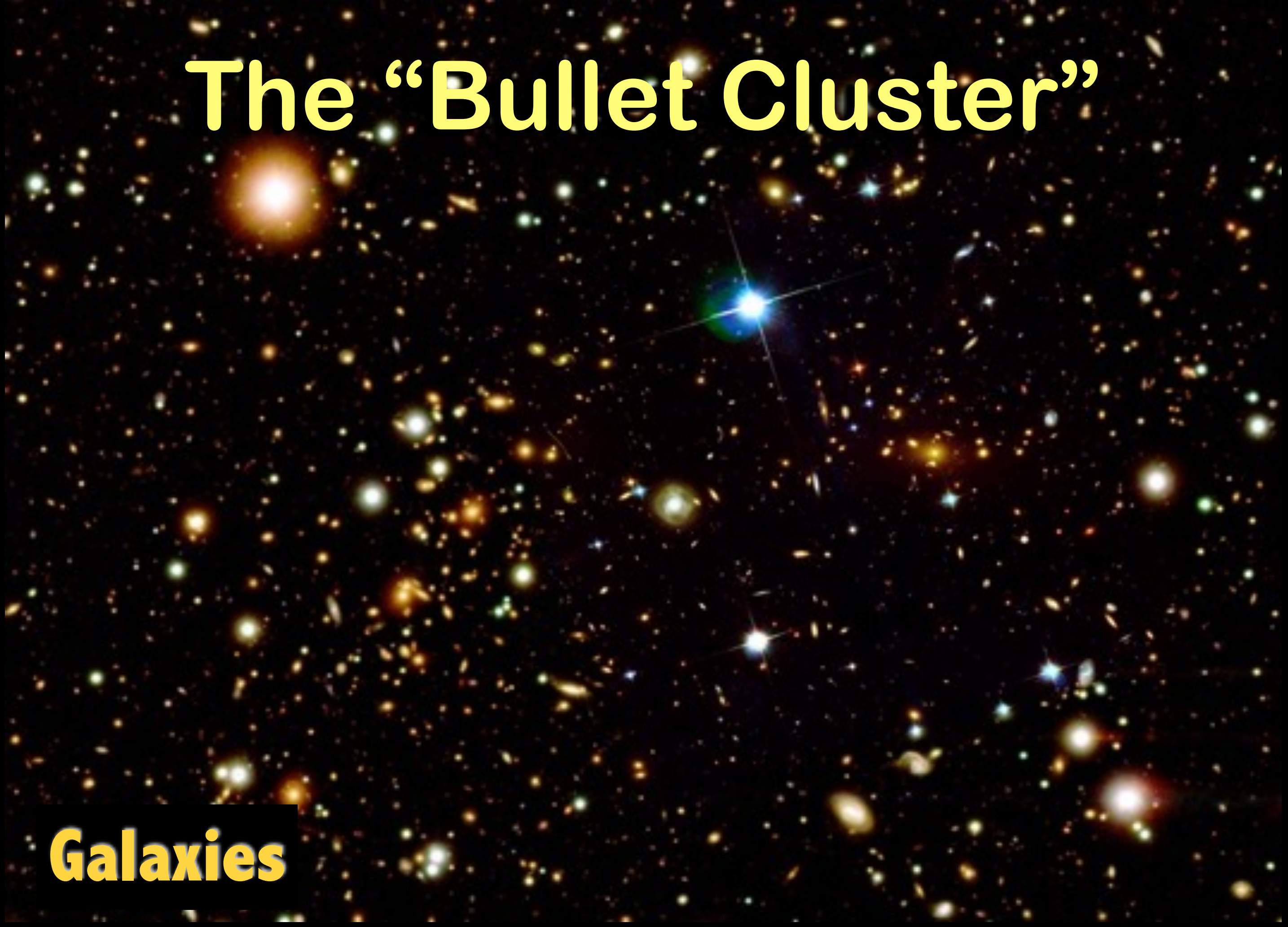


Optical: NASA/STScI, ESO/VLT, SDSS

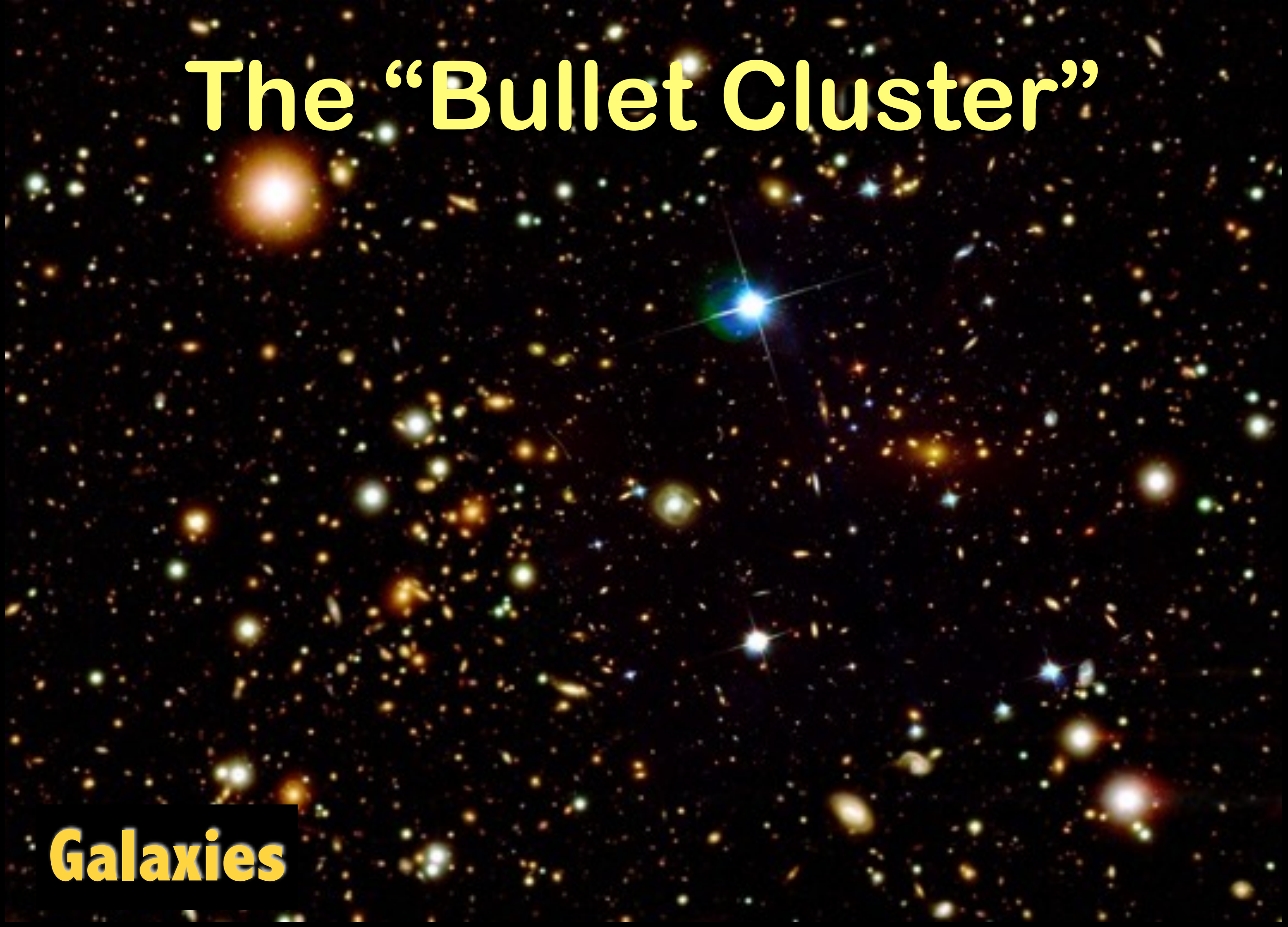
X-ray: NASA/CXC/Caltech/A.Newman et al/Tel Aviv/A.Morandi & M.Limousin


Optical + X-rays

The “Bullet Cluster”



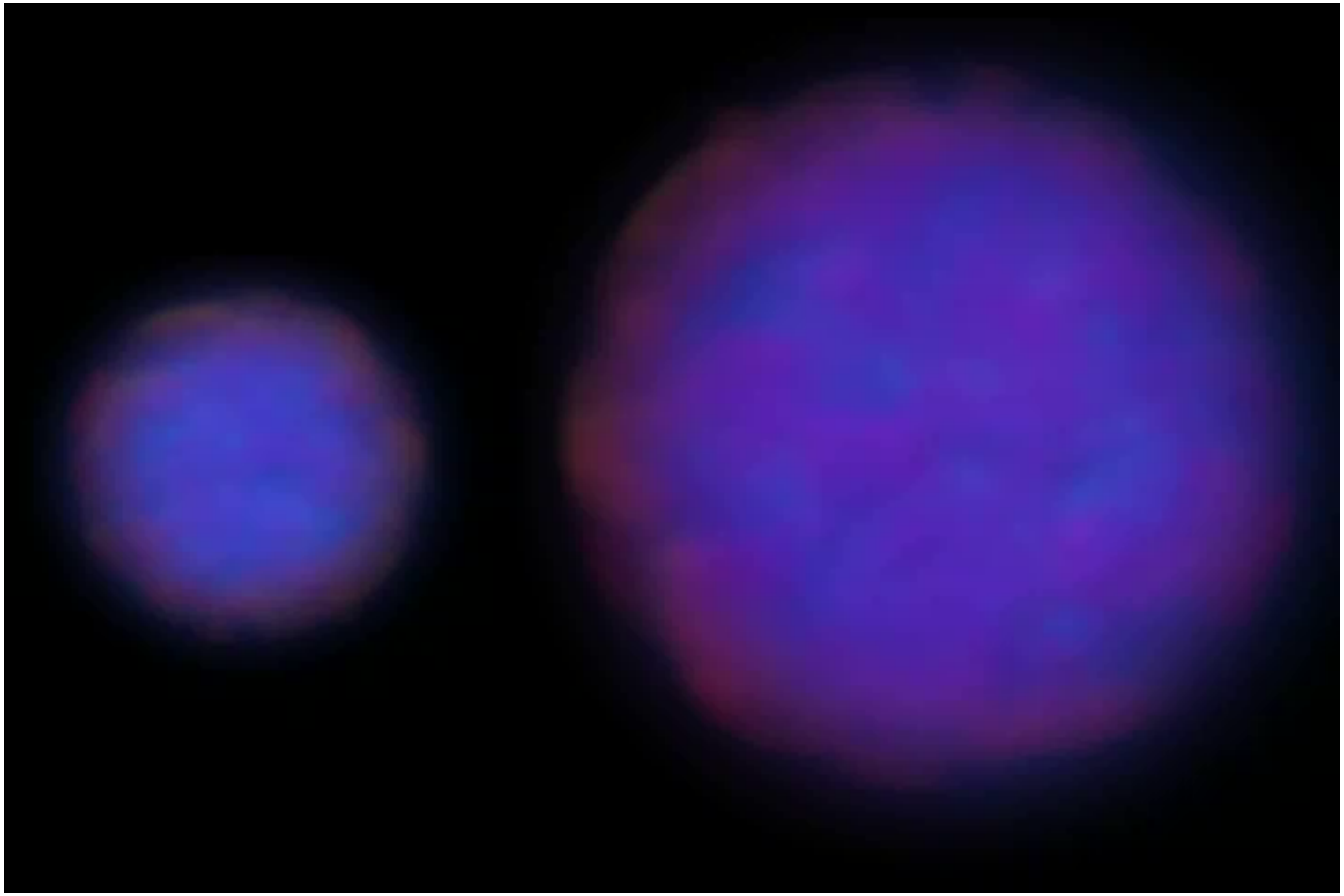
The “Bullet Cluster”



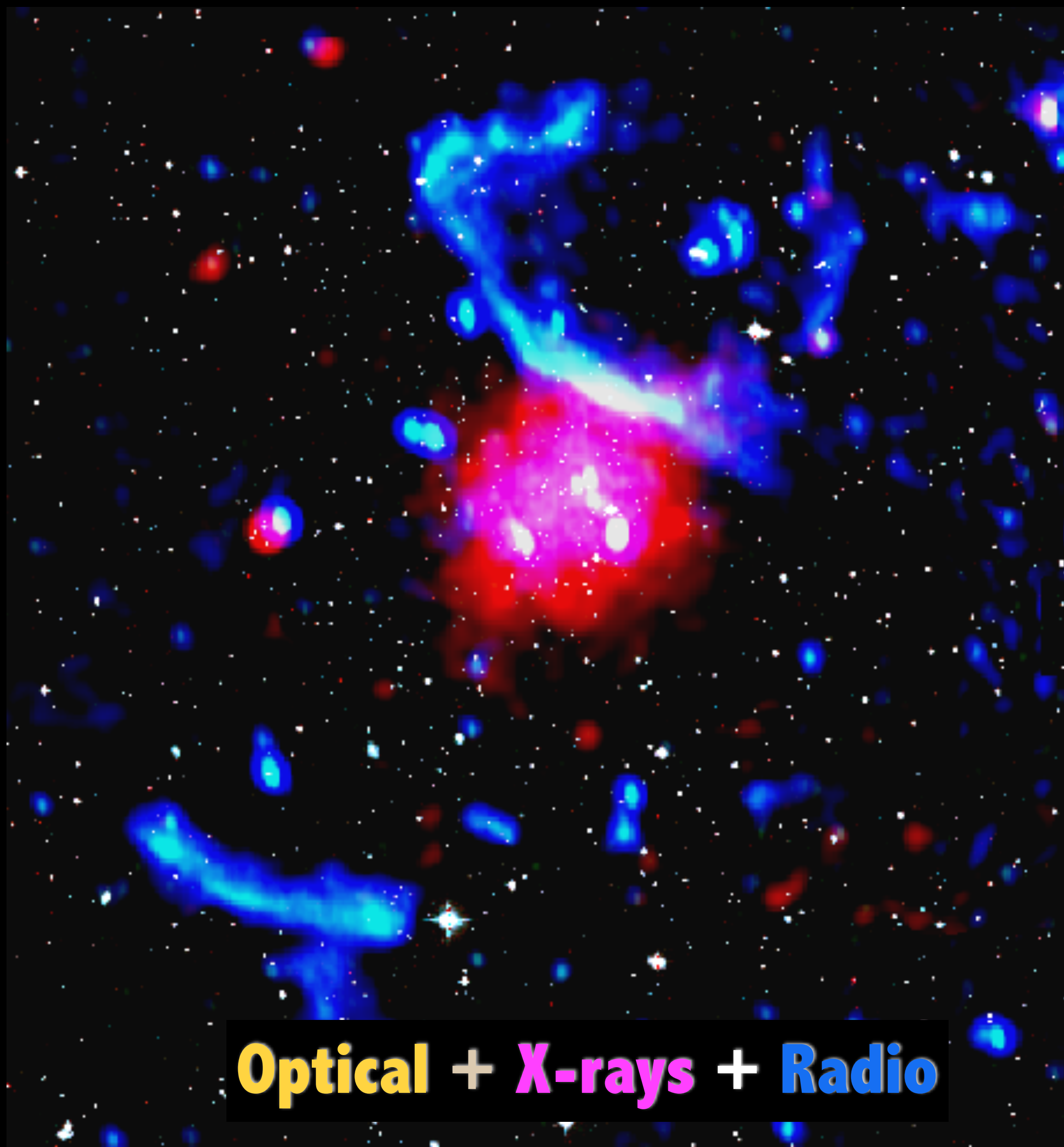
The “Bullet Cluster”

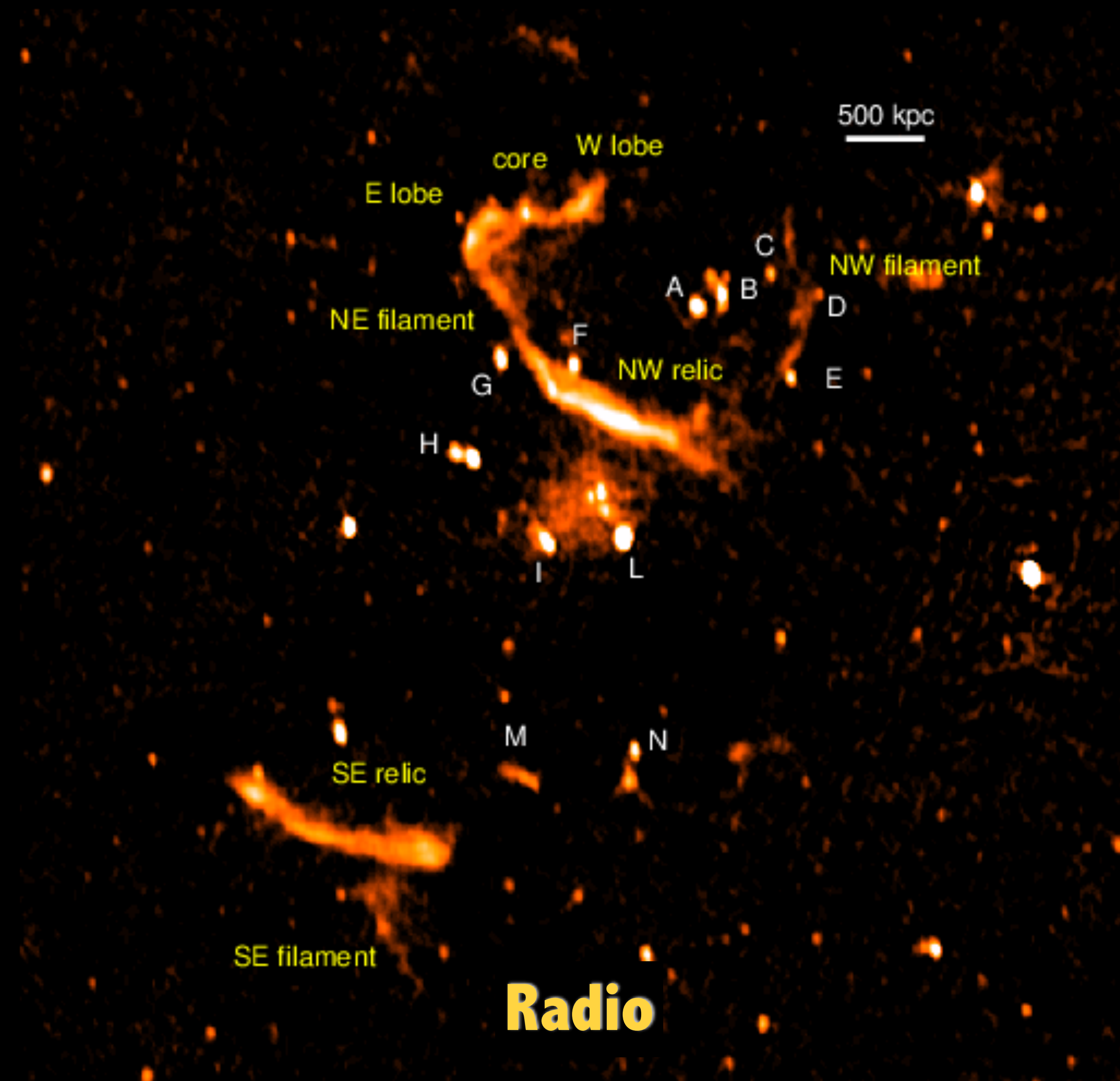
The "Bullet Cluster"

Galaxy cluster formation



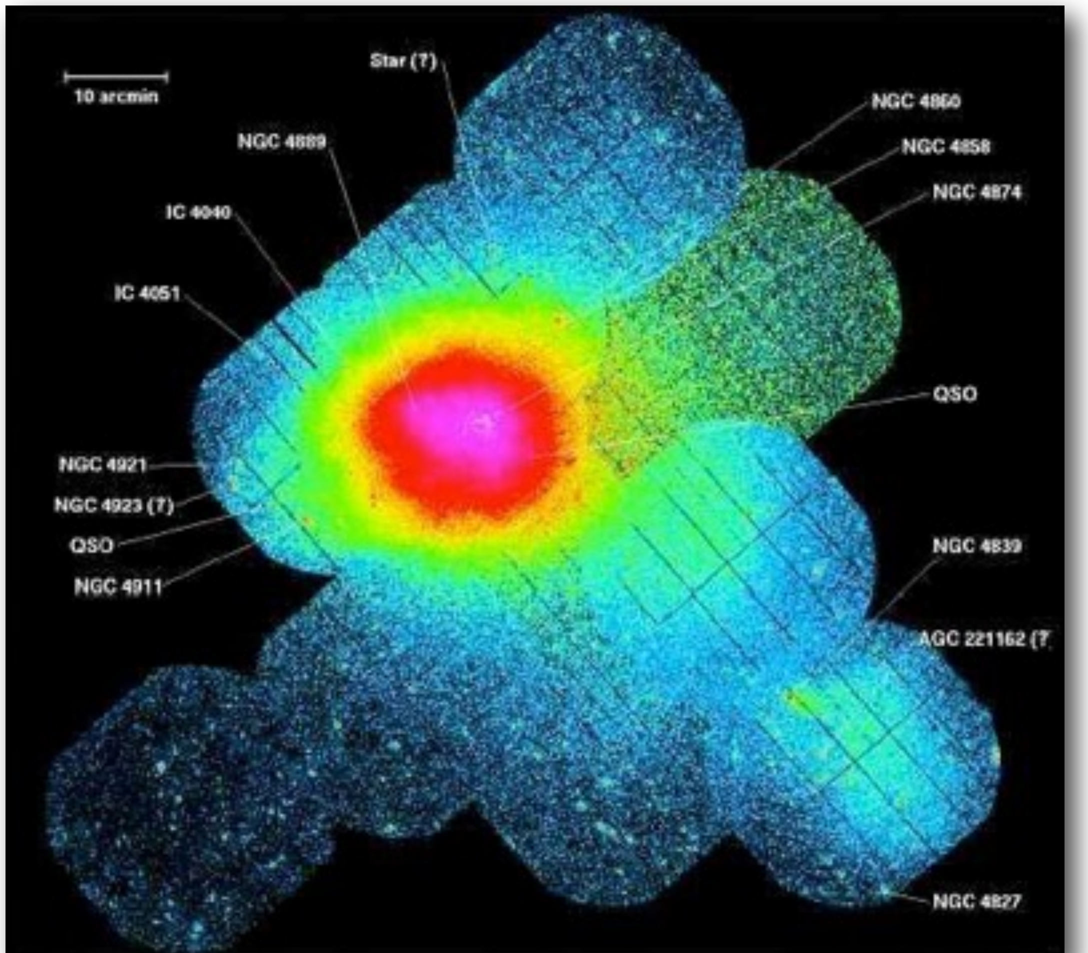
Spectacular radio emission from galaxy clusters





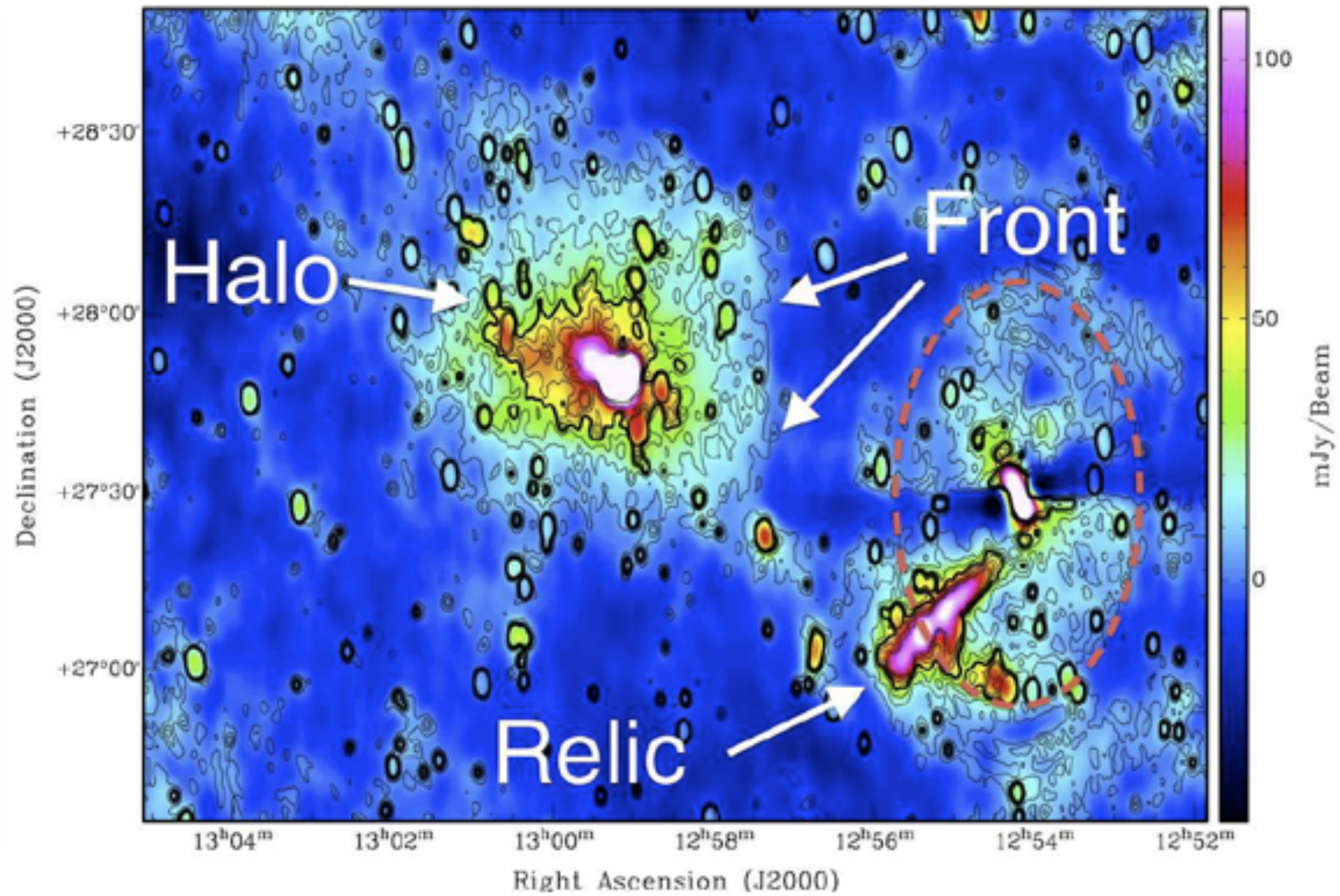
Bonafede et al. 2014

Diffuse radio emission in clusters



The Coma cluster observed by XMM

Neumann+ 01

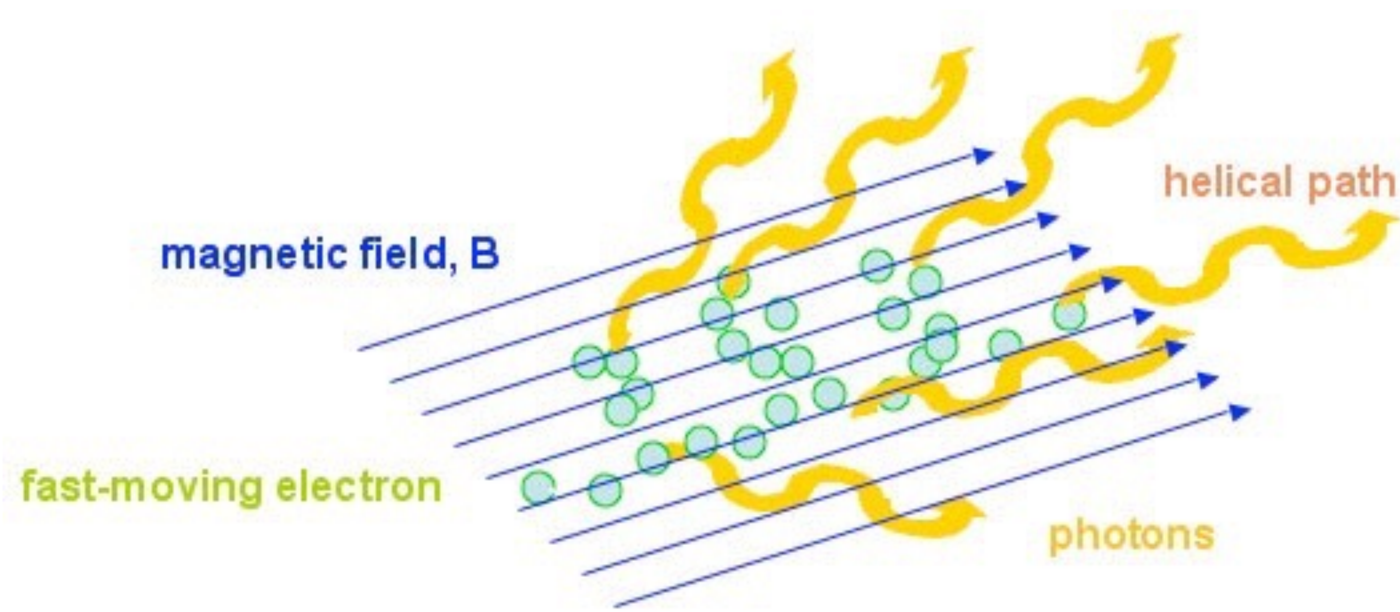


The Coma cluster observed at 352 MHz with WSRT

Brown & Rudnick 11

→ *Detected in less than 10% of known clusters (="radio loud")*

Intra-cluster magnetic fields



<u>Magnetic fields:</u>

- ubiquitous in galaxy clusters
- same properties regardless of the presence of diffuse radio emission

(e.g. Bonafede+ 11)

→ *The difference between "radio-quiet" and "radio-loud" clusters appears to be in their relativistic electron population*

Intra-cluster primary cosmic rays

Primary cosmic rays

protons (CRPs) & electrons (CREs)

Internal processes

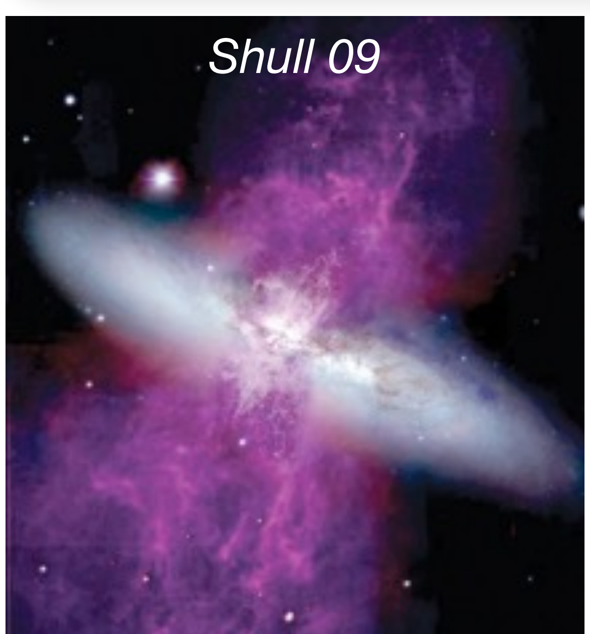
CRs accelerated inside cluster galaxies and then injected

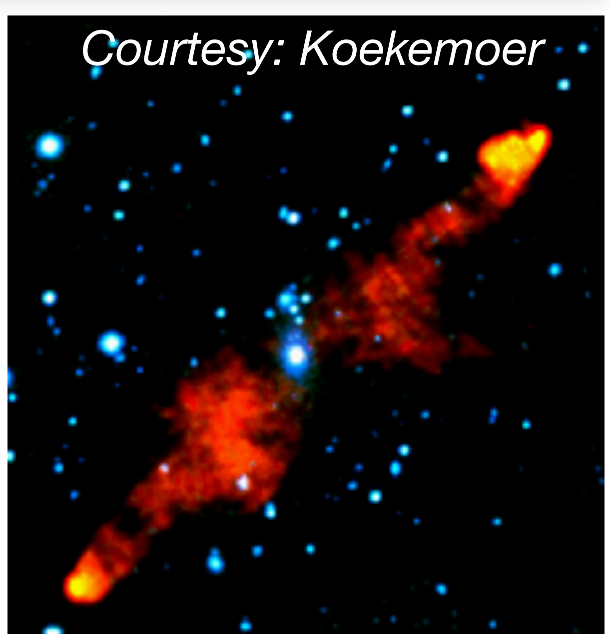
- SNae driven galactic winds
- AGNs

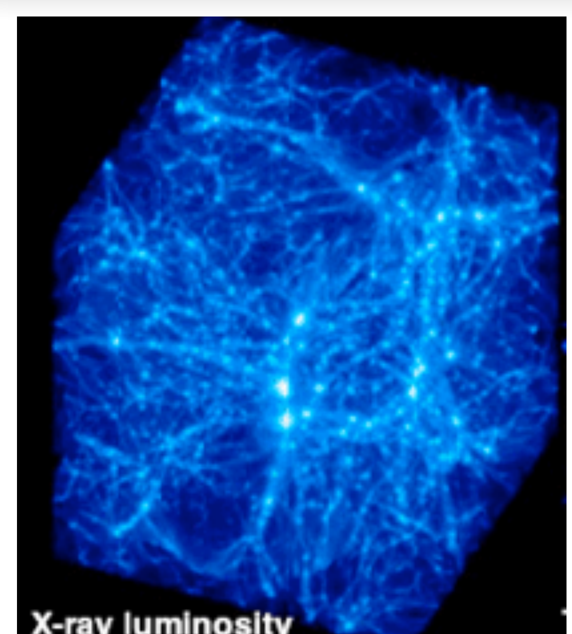
External processes

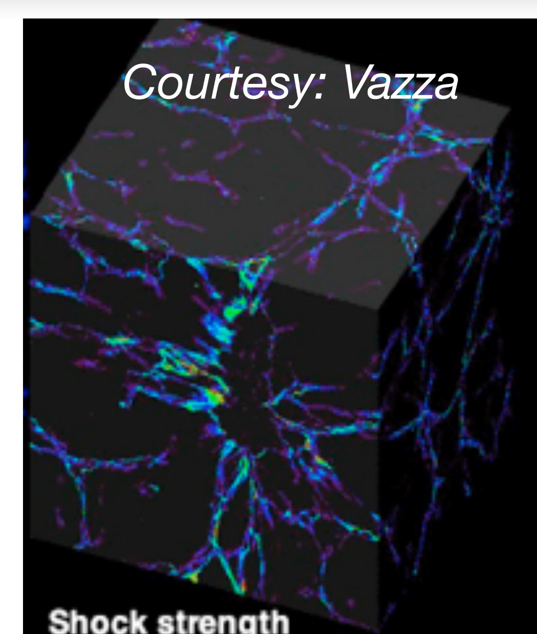
CRs acceleration driven by the assembly of clusters

- accretion shocks (M ~ 10^3)
- merging shocks (M ~ 3-10)
- ICM turbulence

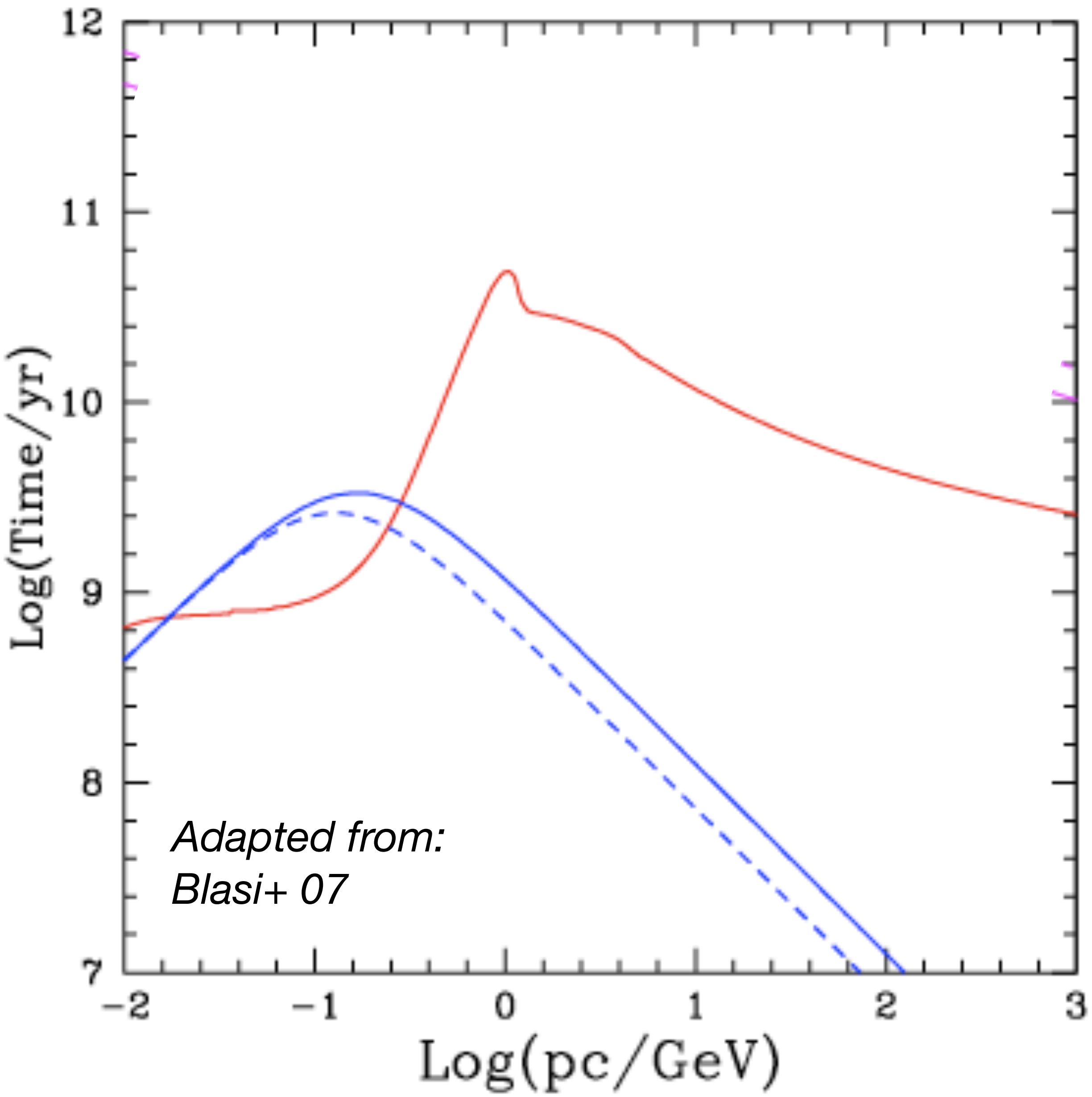








Lifetime of intra-cluster cosmic rays

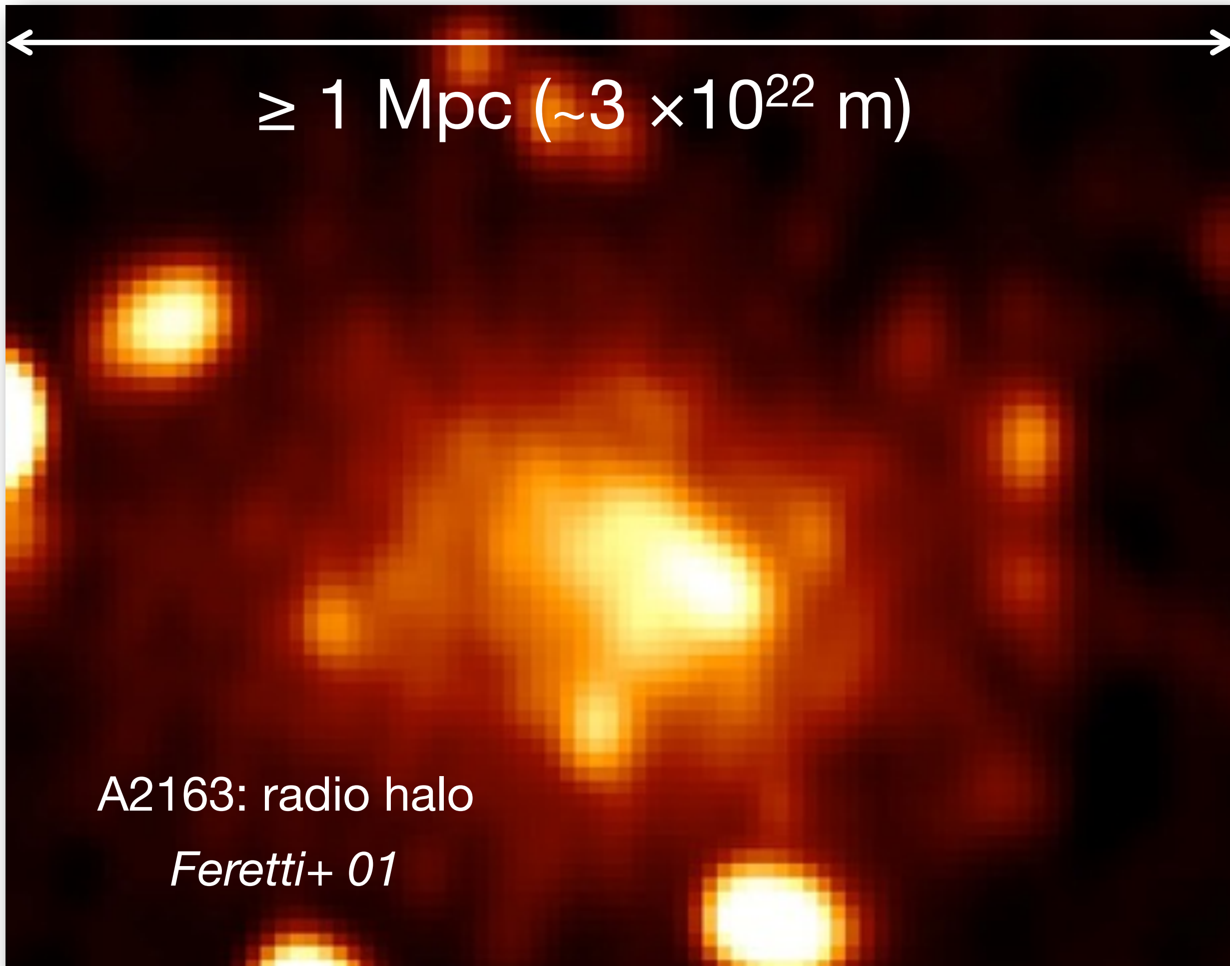


Adapted from:
Blasi+ 07

The lifetime of cosmic-rays in clusters depends on diffusion and energy losses time scales

- Time scales for proton energy losses
- Time scales for electron energy losses

Origin of radio emitting relativistic electrons ?



Dimensions: ~ 1 Mpc

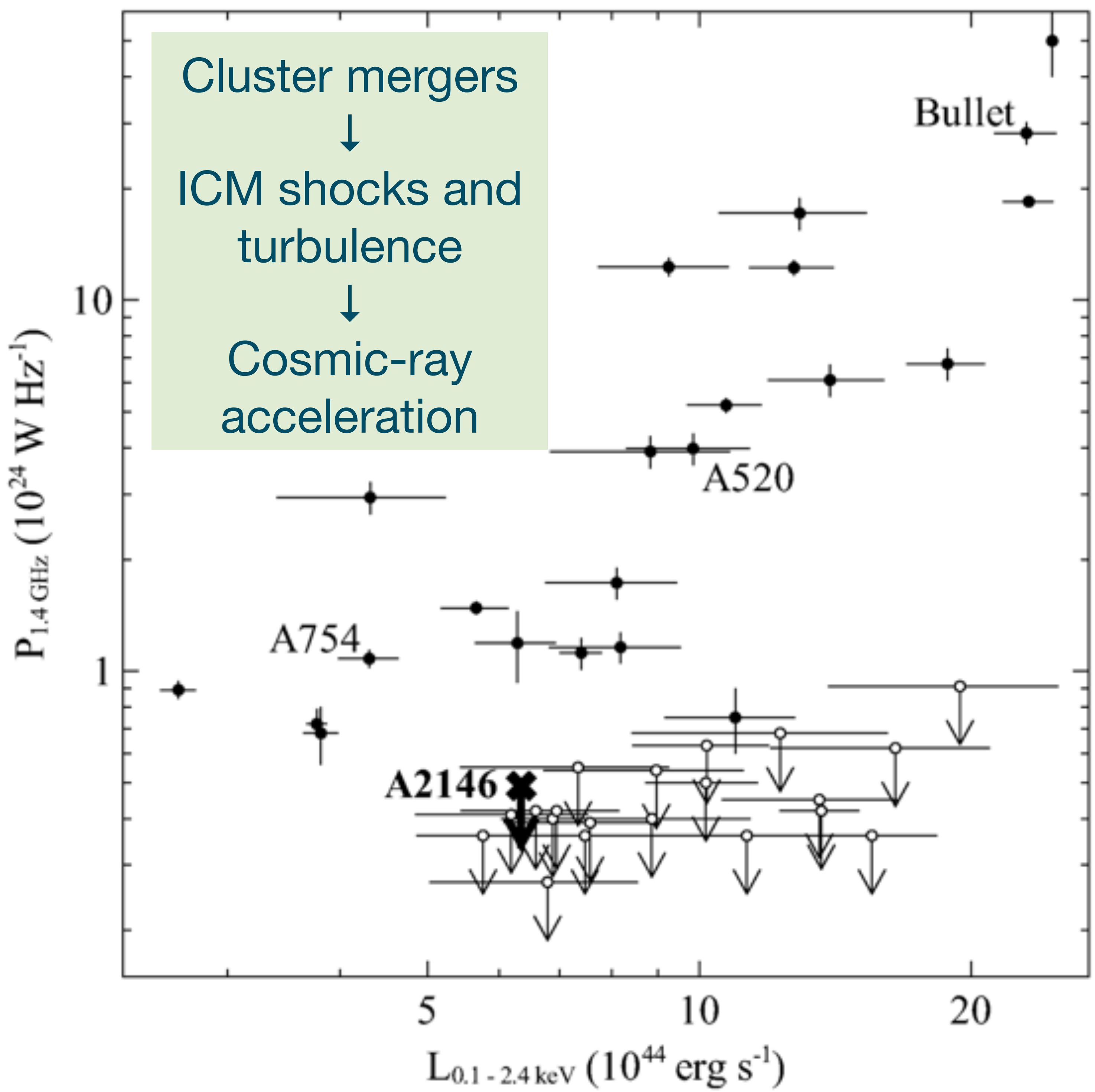
Crossing time of e^-: ~9.5 Gyr

Life time of e^-: ~ 0.1 Gyr

(e.g. Ferrari+ 08)

→ *Spatially distributed acceleration of primary electrons through shocks and turbulence associated to* ***cluster mergers***

Which clusters host Mpc-scale radio sources?



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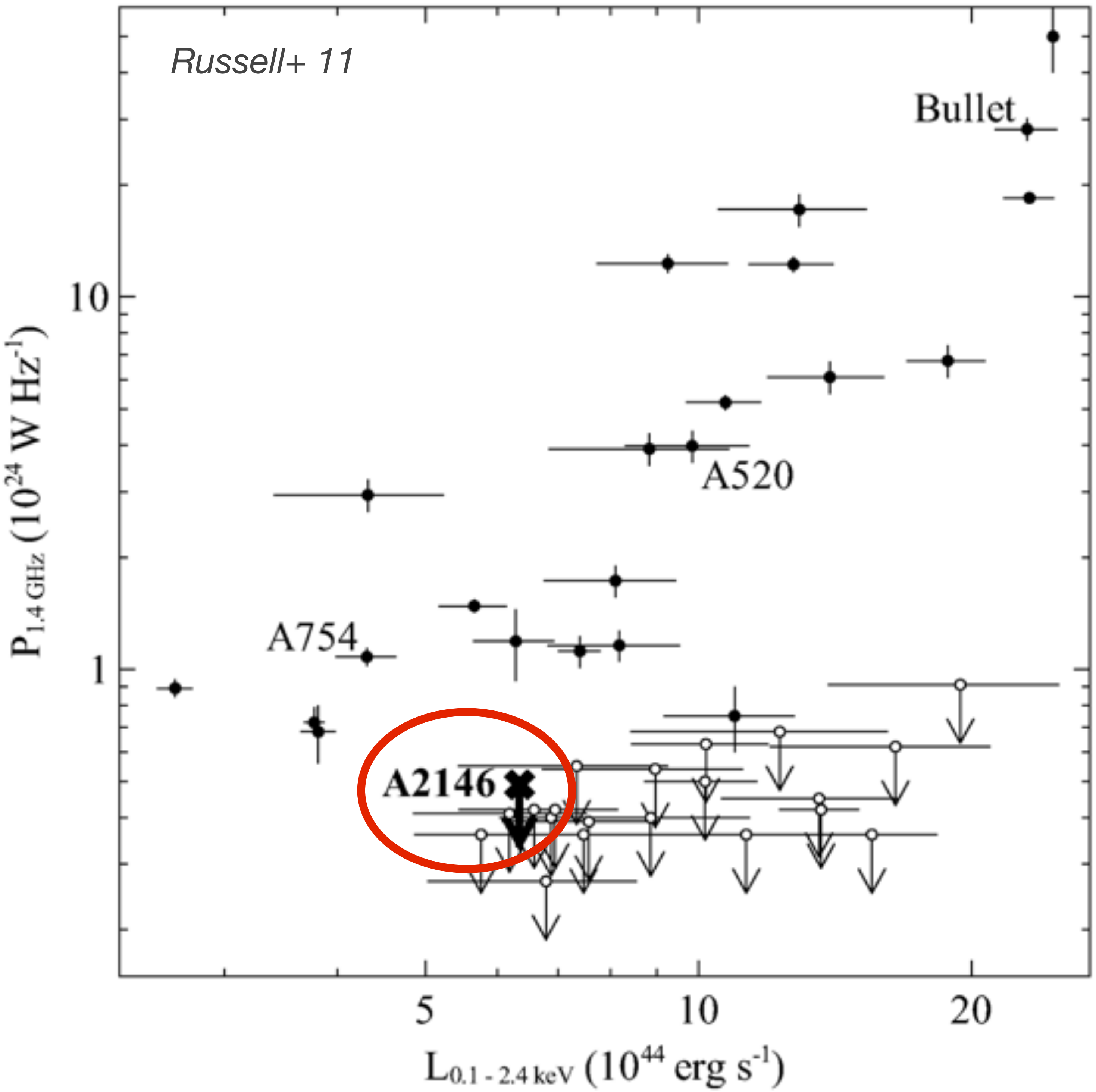

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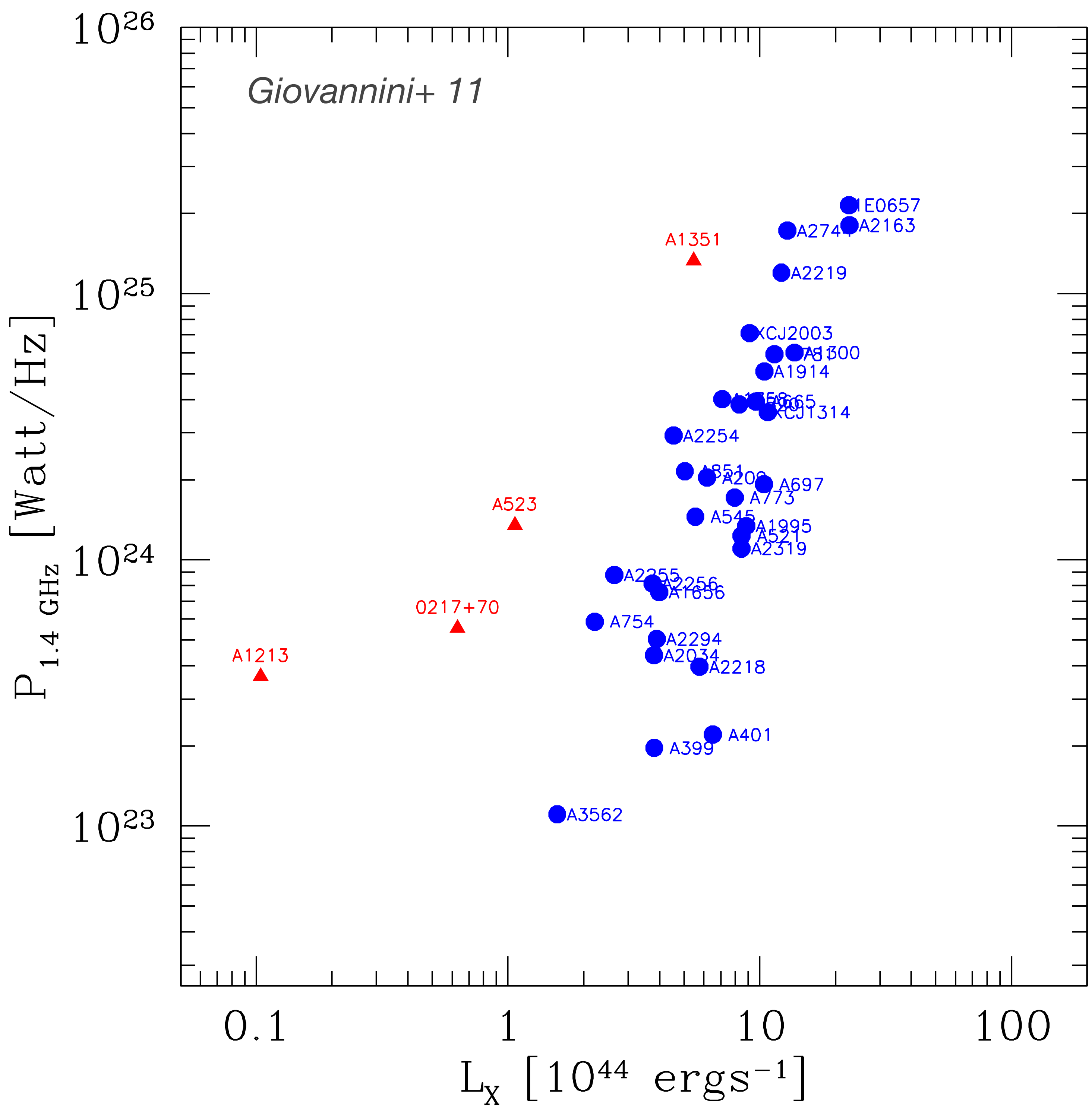
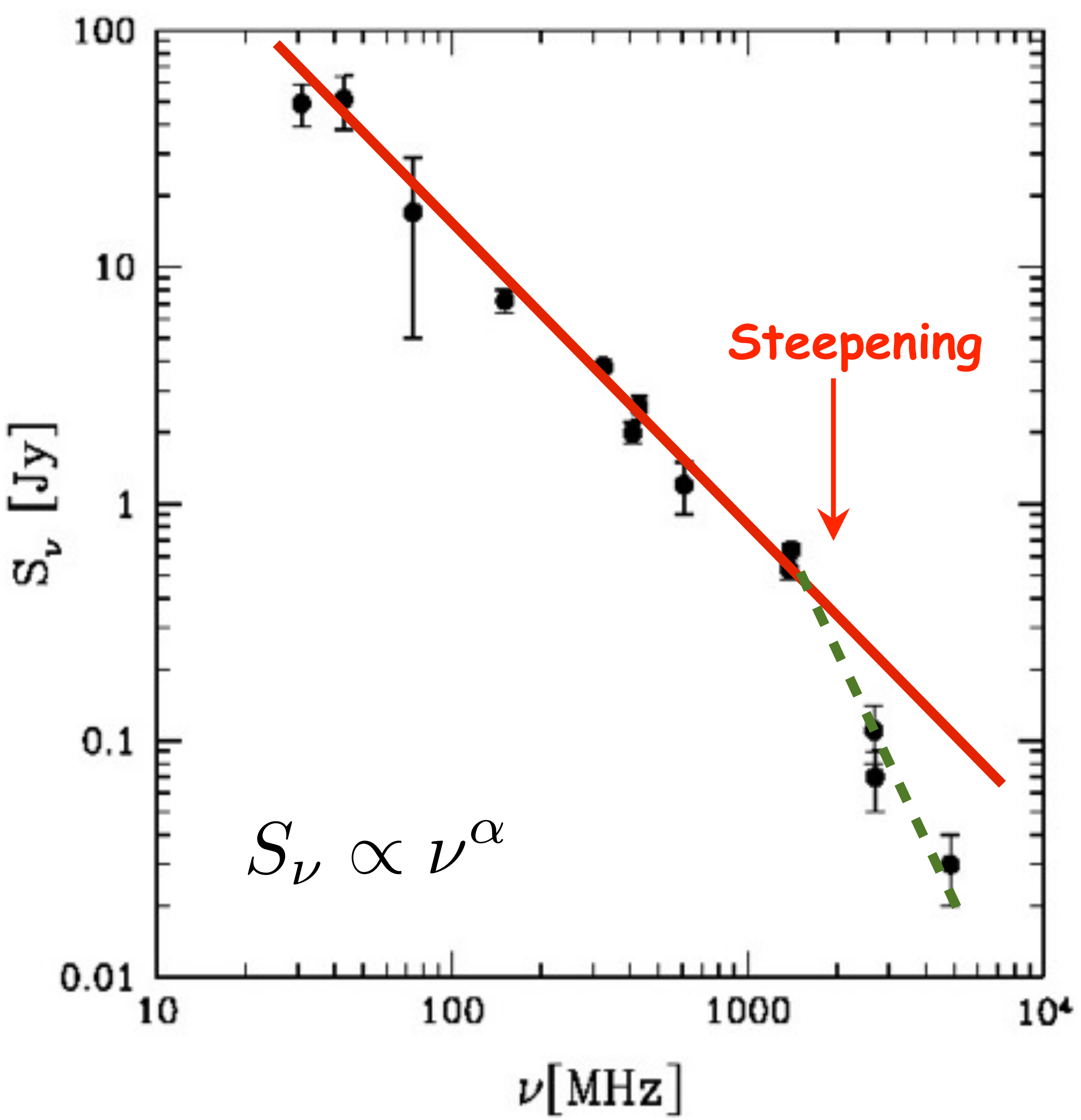


Importance of low frequency observations



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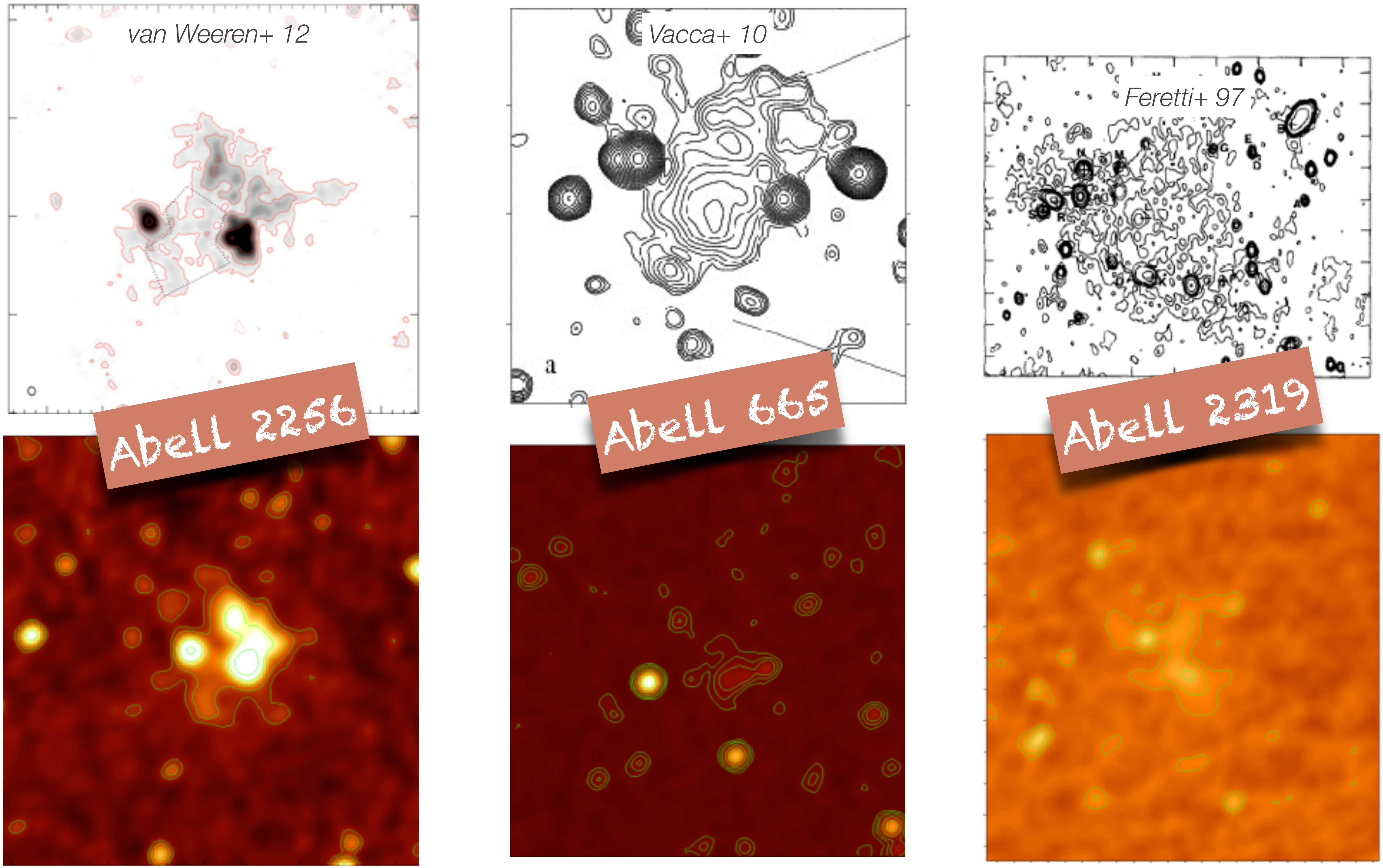
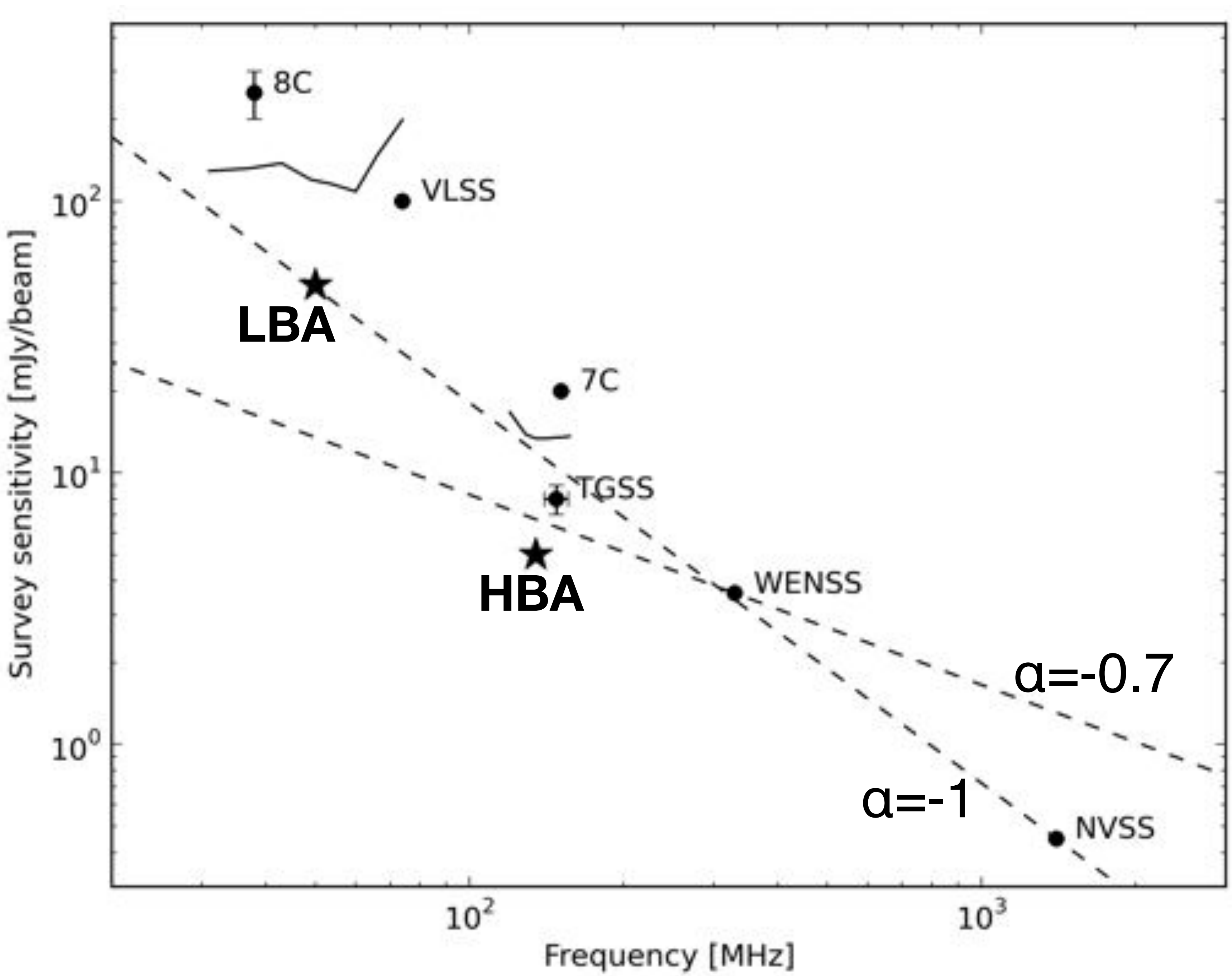
Galaxy clusters & MSSS



MSSS sensitivity



Heald+ submitted

LOFAR Key Project Surveys

Large Area Survey (Tier 1)

2π ster. @ 15, 30, 60, 120 MHz

783 deg^2@ 200 MHz

→ 100 galaxy clusters @ z > 0.6

→ 200 radio-galaxies @ z > 7

Deep Area Survey (Tier 2)

Several hundreds deg^2 @ 30, 60, 120, 200 MHz

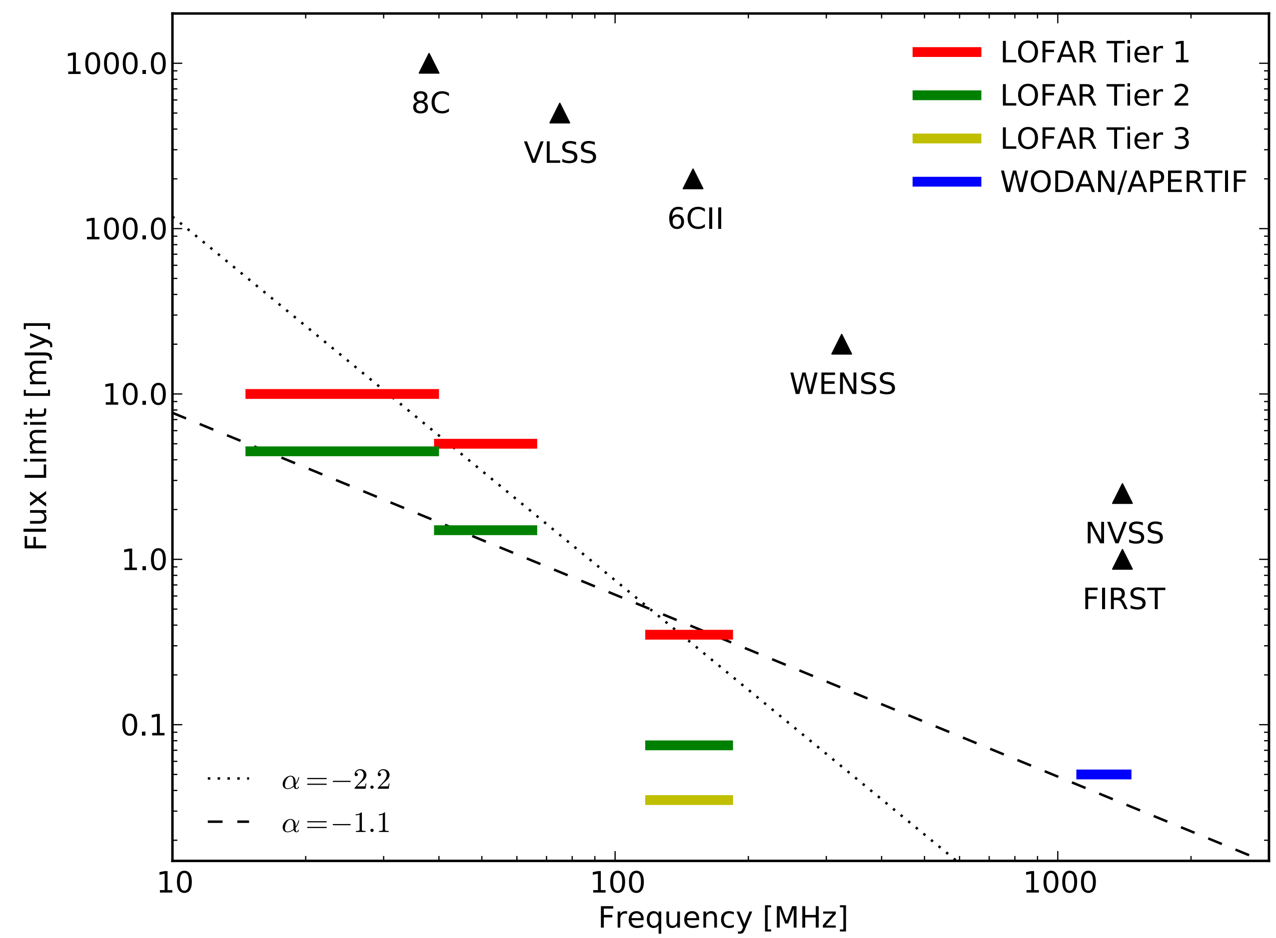
→ SFR ≥ 10 M_{Sun}/yr @ z = 0.5

→ SFR ≥ 100 M_{Sun}/yr @ z = 2.5

Ultra-Deep Area Survey (Tier 3)

~70 deg^2 @ 150 MHz

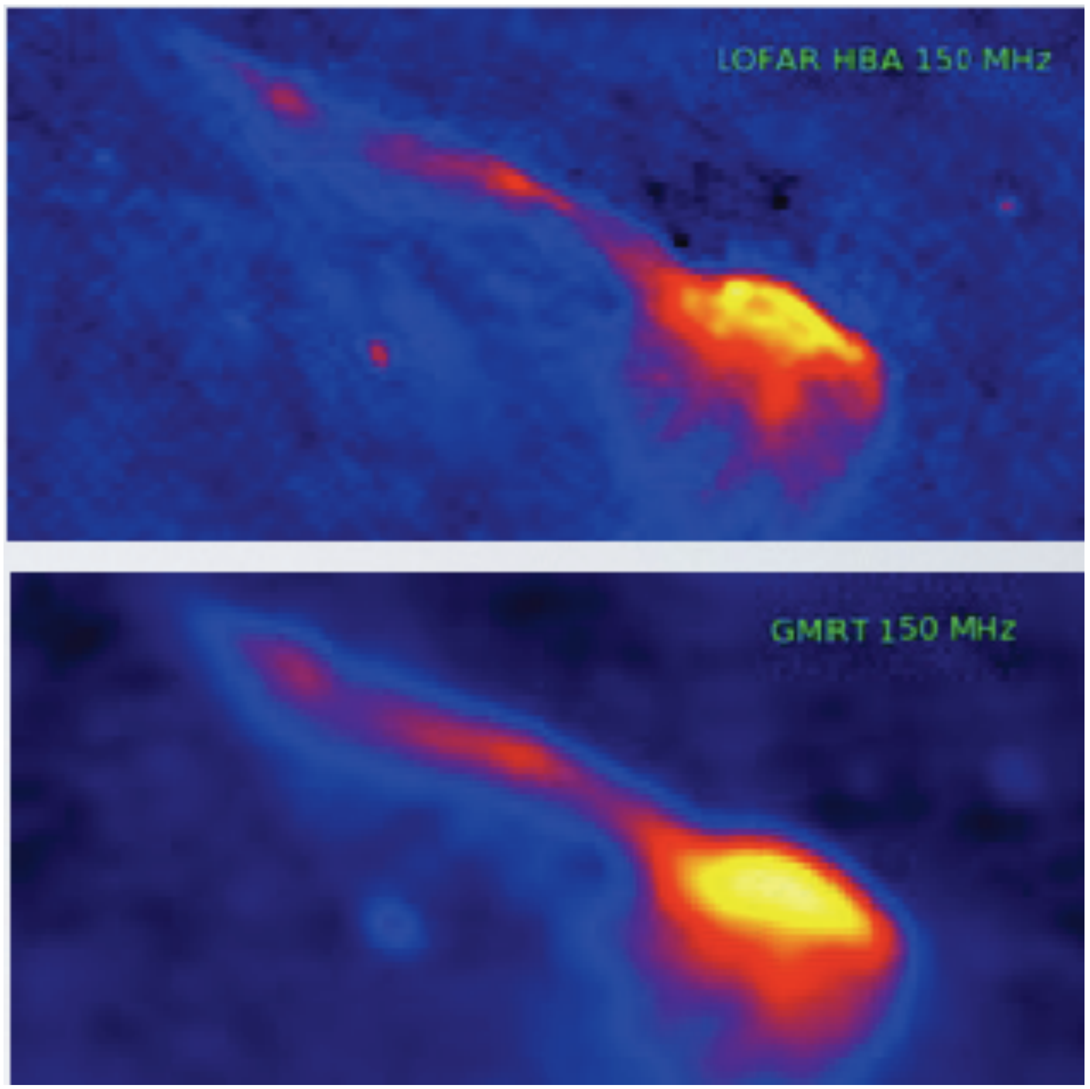
→ 20 proto-clusters @ z > 2



Courtesy: H. Röttgering

On-going LOFAR Surveys

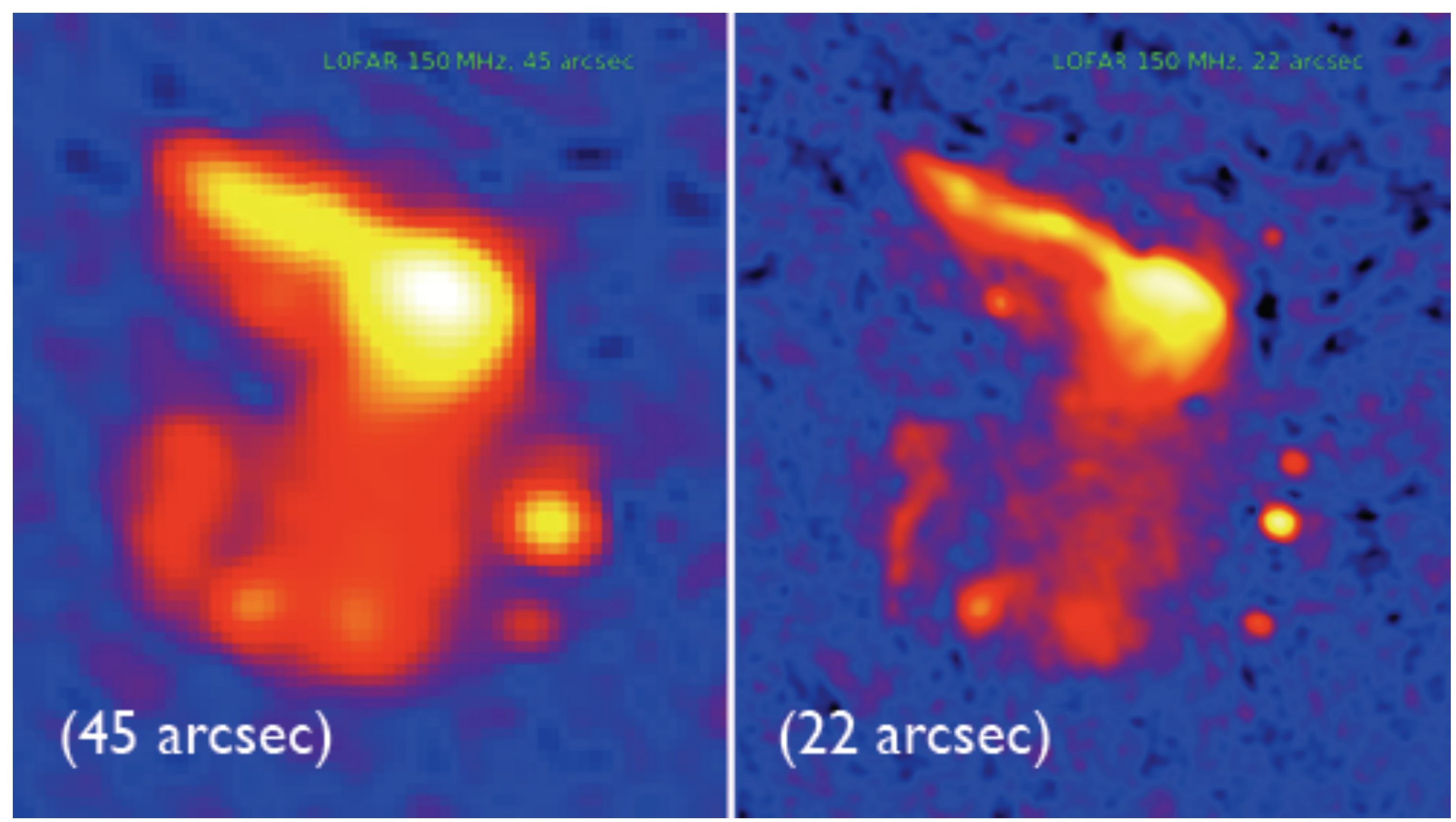
LOFAR Cycles 0-1



Full resolution (5x7 arcsec), 140-160 MHz
close to thermal noise (190-250 microJy/beam)

Only 30% of available bandwidth !

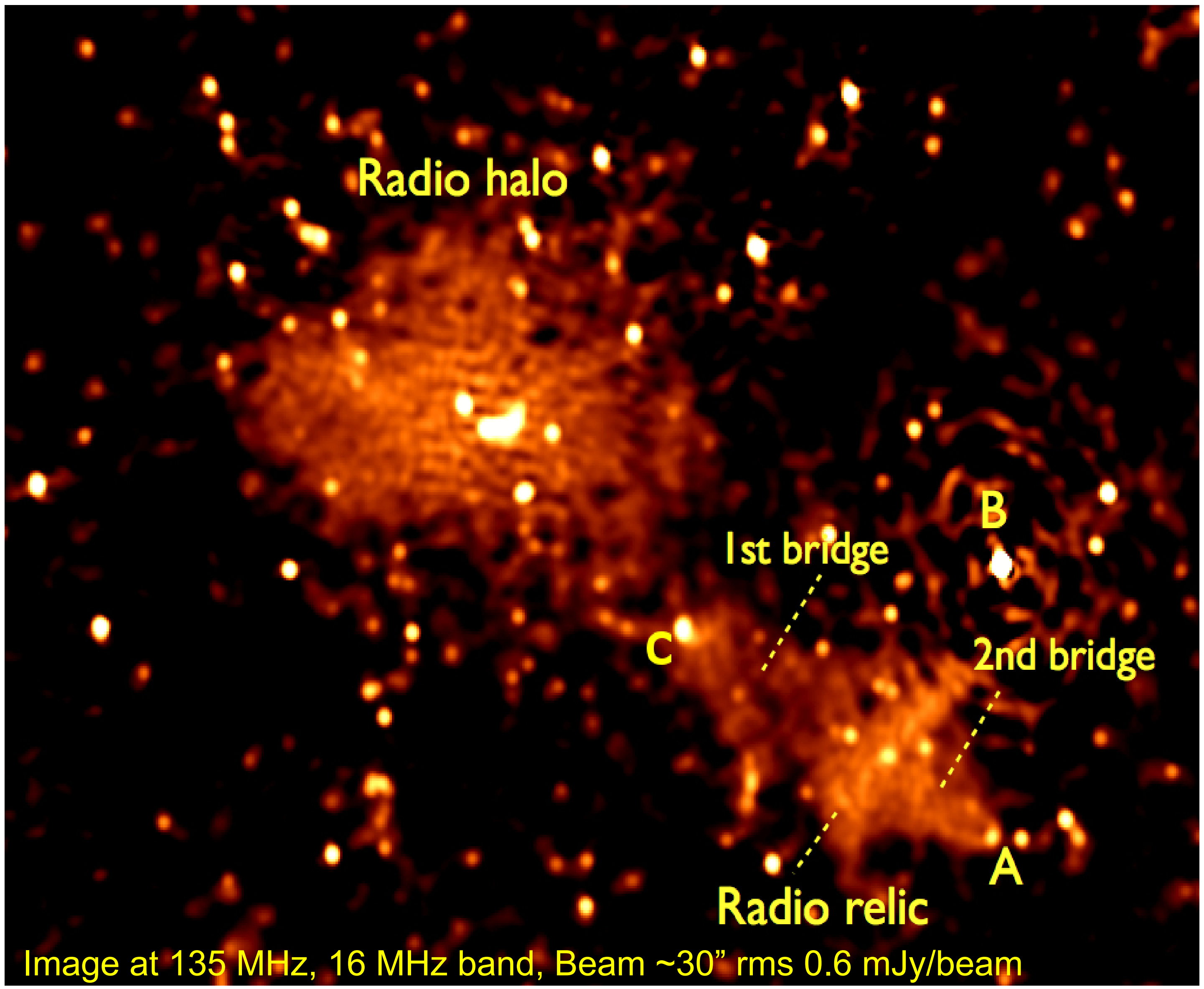
Images by R. van Weeren
(Toothbrush Galaxy Cluster)

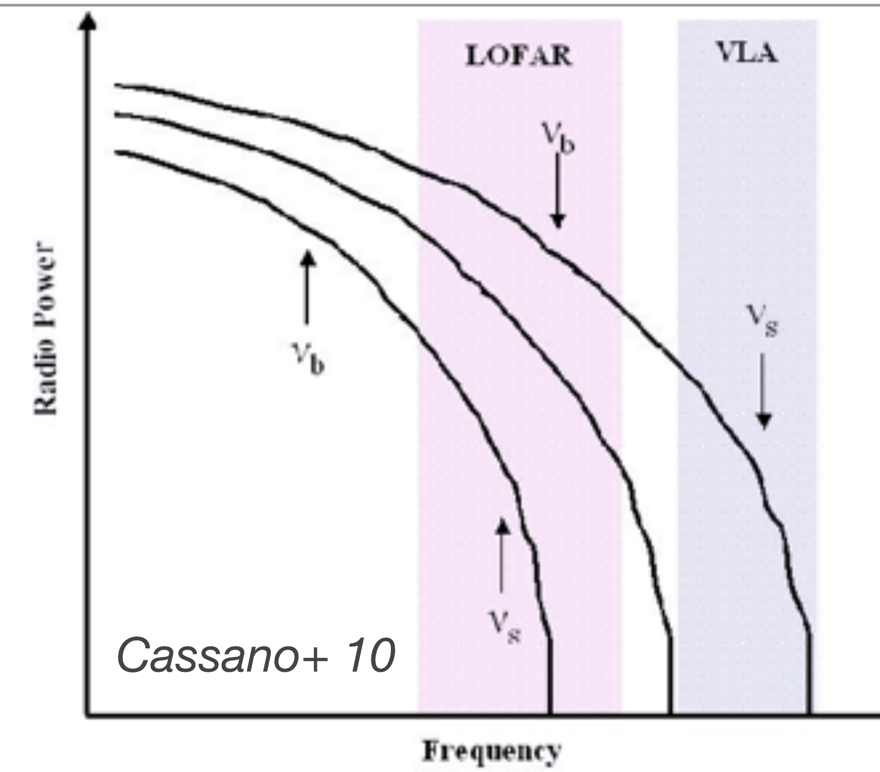


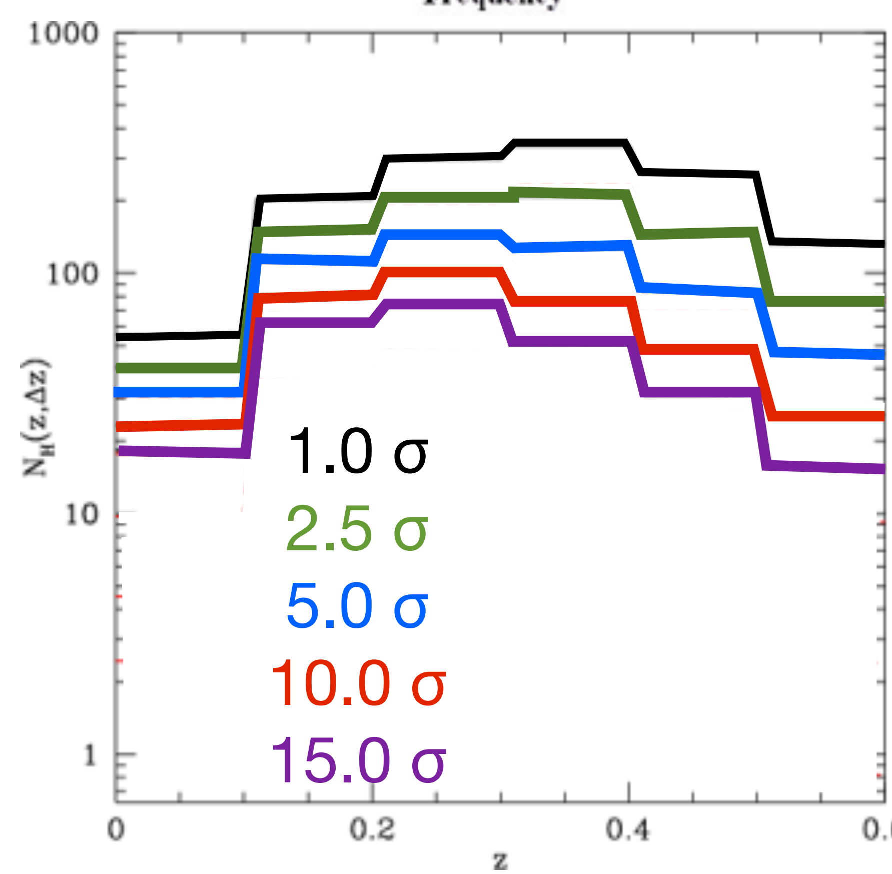
Courtesy: H. Röttgering & LOFAR Surveys KP

On-going LOFAR Surveys

LOFAR Cycles 0-1







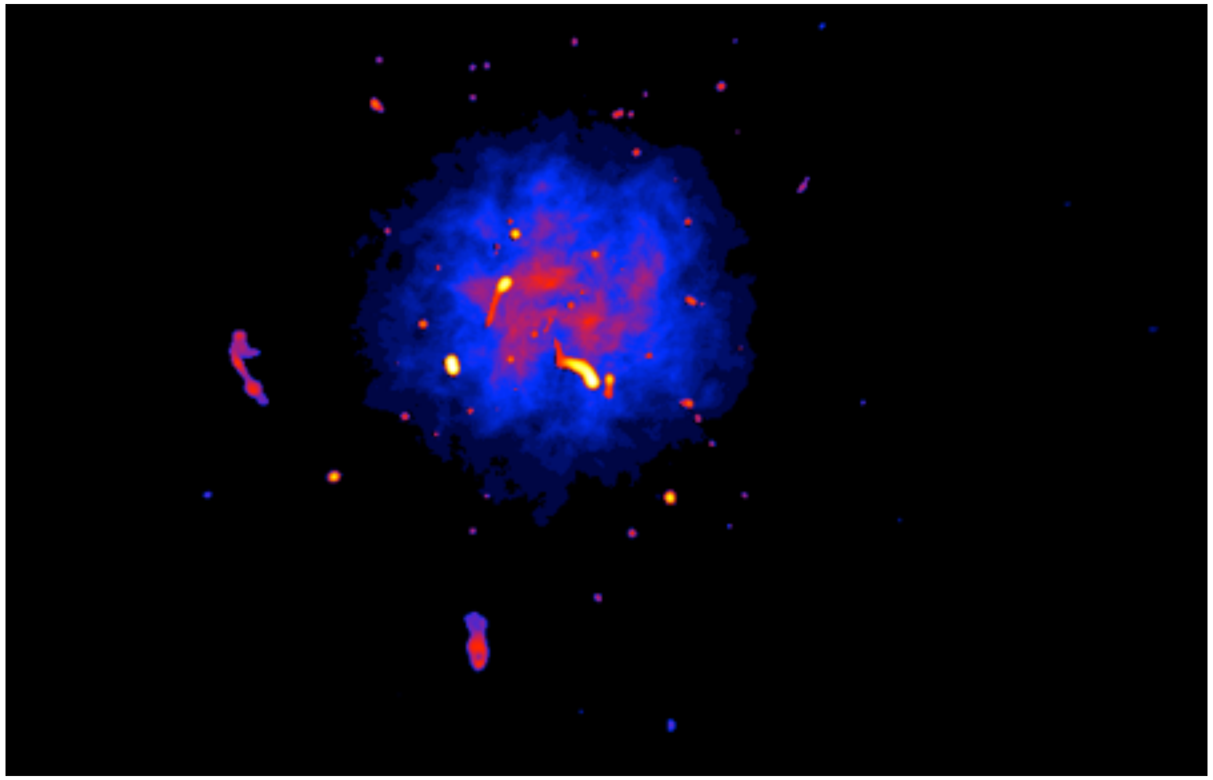
Courtesy: A. Bonafede for the LOFAR galaxy cluster group

Diffuse radio emission from galaxy clusters with SKA1

Radio galaxies +

Radio halo ($P_{1.4\ GHz} \sim 1 \times 10^{24}$ W/Hz)

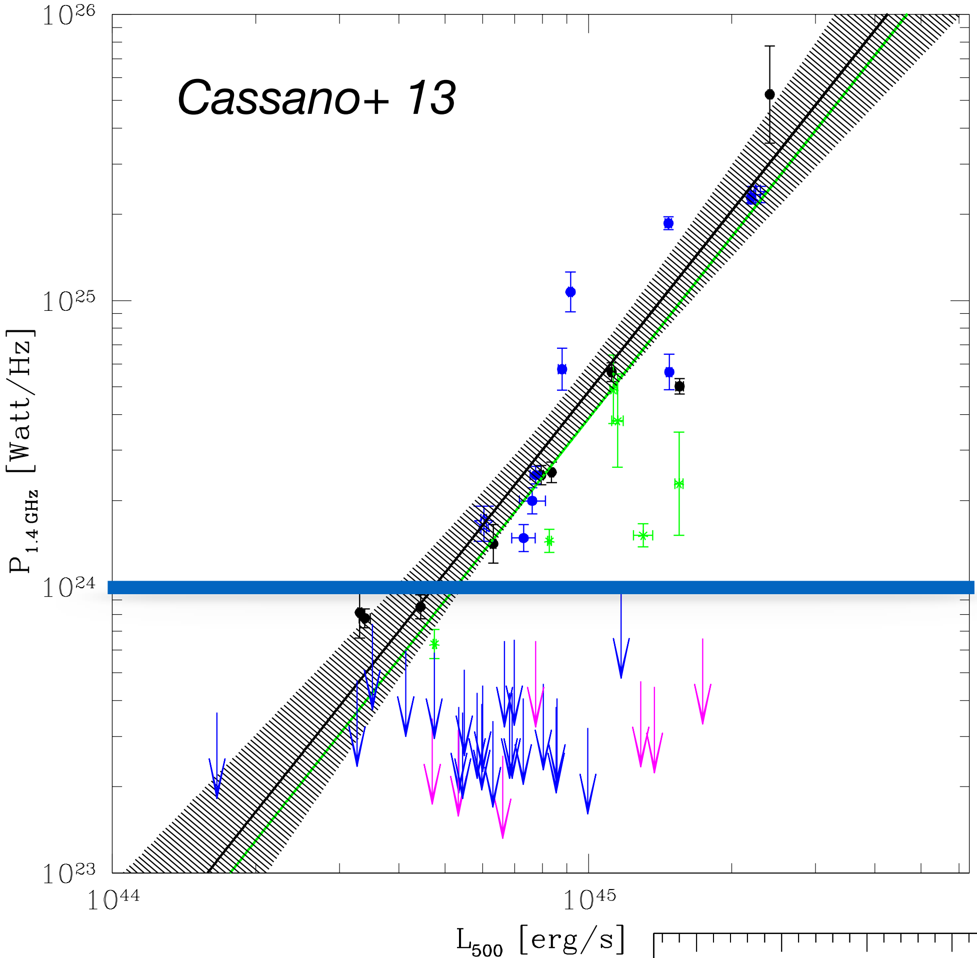
@ $z \geq 0.5$

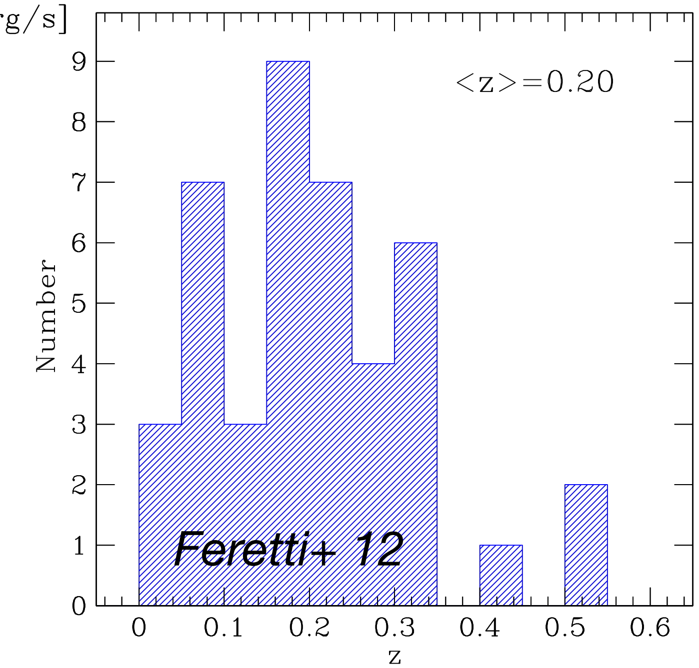


Relativistic electron population

+ Magnetic field model

Faraday tool *(Murgia+ 04)*





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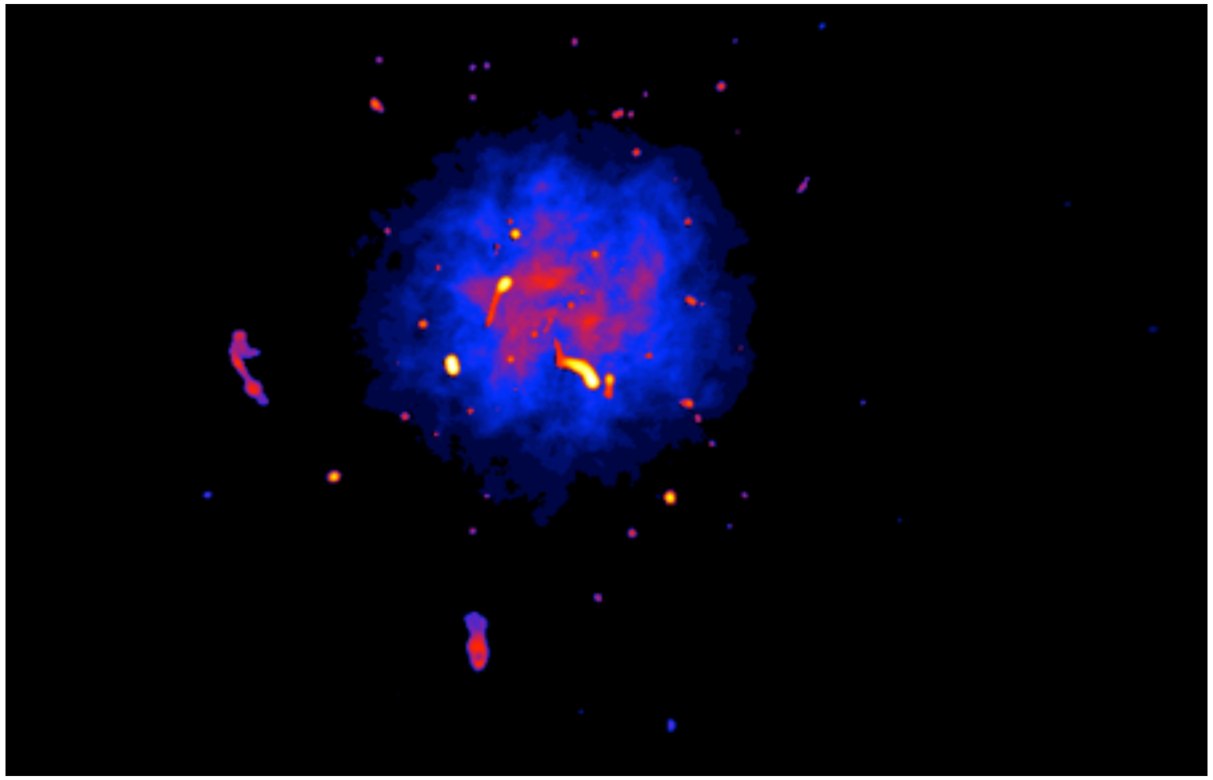
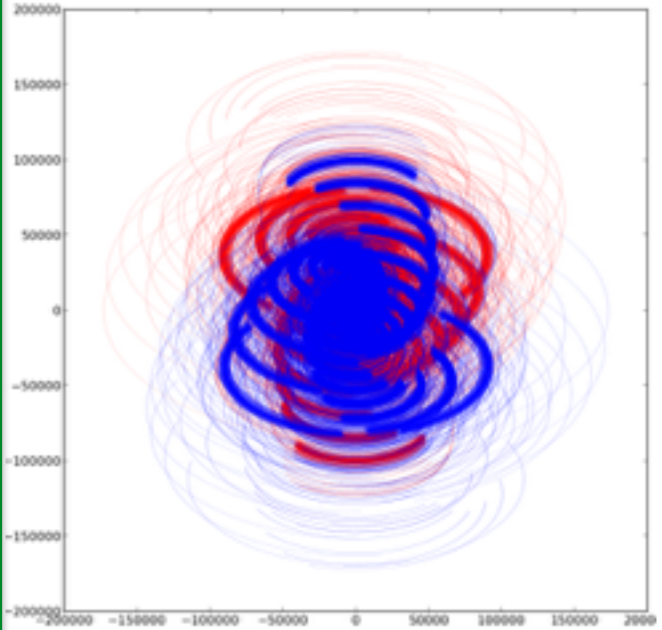


8 hours observations

60 sec integration time

50 MHz BW starting @ 1415 MHz



Relativistic electron population

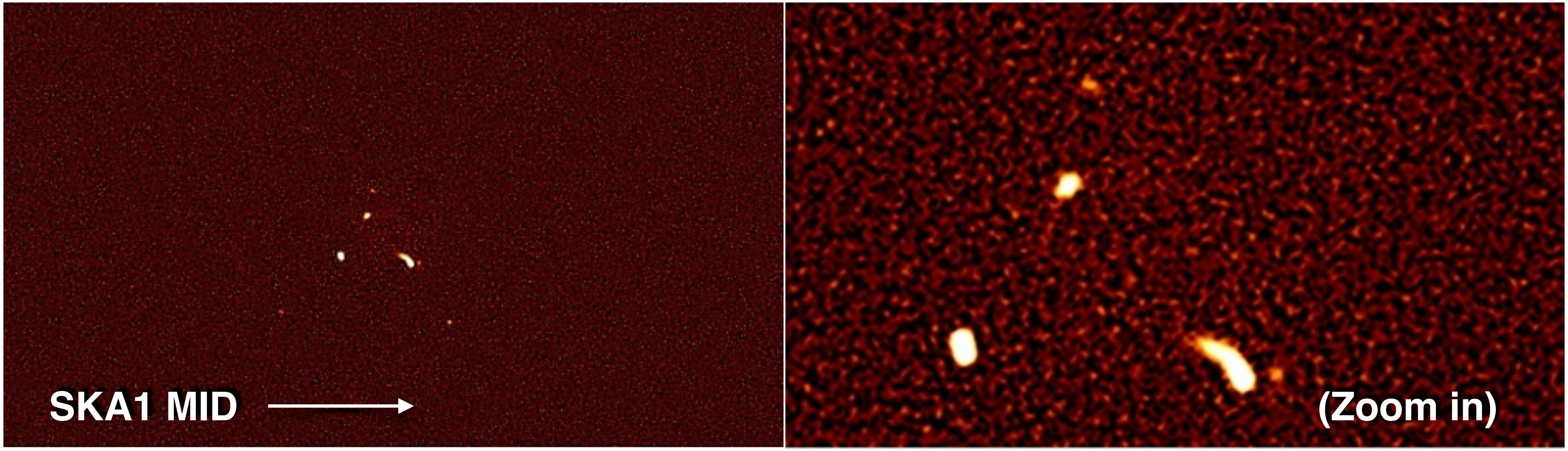
+ Magnetic field model

Faraday tool (Murgia+ 04)

Simulations of SKA1 MID & SUR observations

MeqTrees tool (Noordam & Smirnov 10)

Simulated SKA1-MID observations



Radio maps before deconvolution from the instrument PSF

1 arcsec resolution

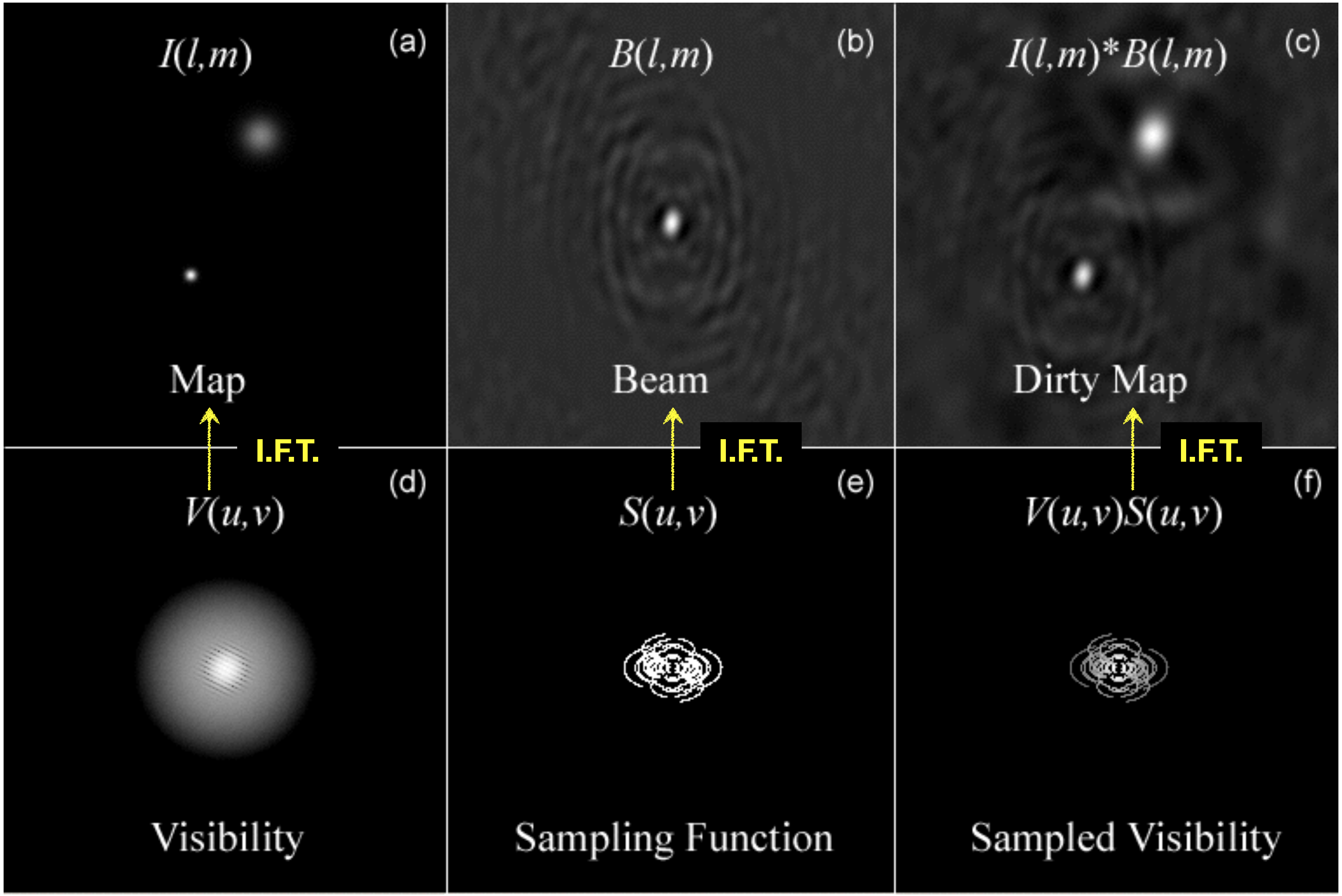
Ferrari+ 15

MORESANE algorithm :

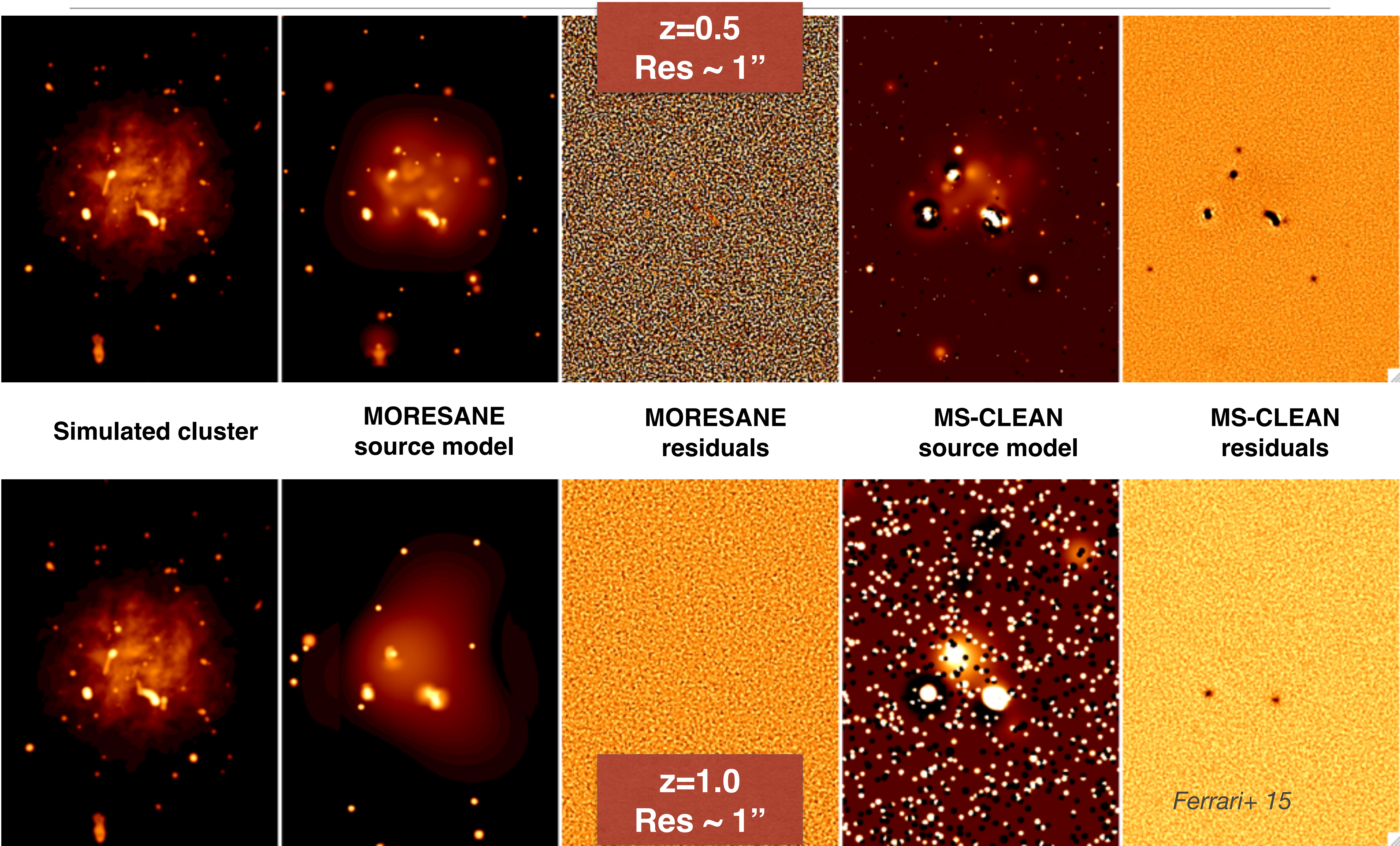
new deconvolution method based on sparse representations developed @ OCA, Nice (FR)

Dabbech+ 12; Dabbech+ 15

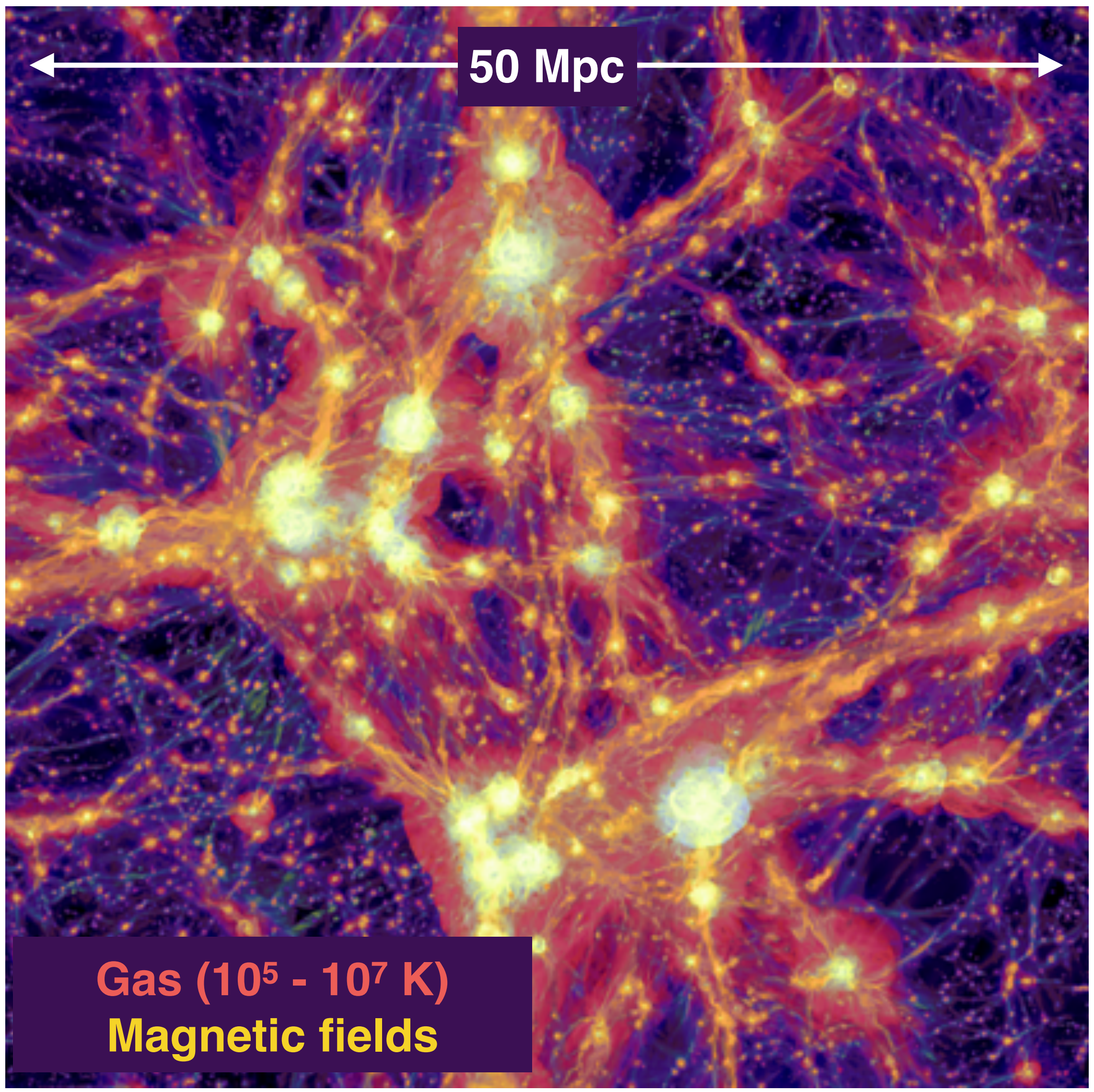
From visibilities to radio images



Up to which redshift can we detect clusters with SKA1-MID ?

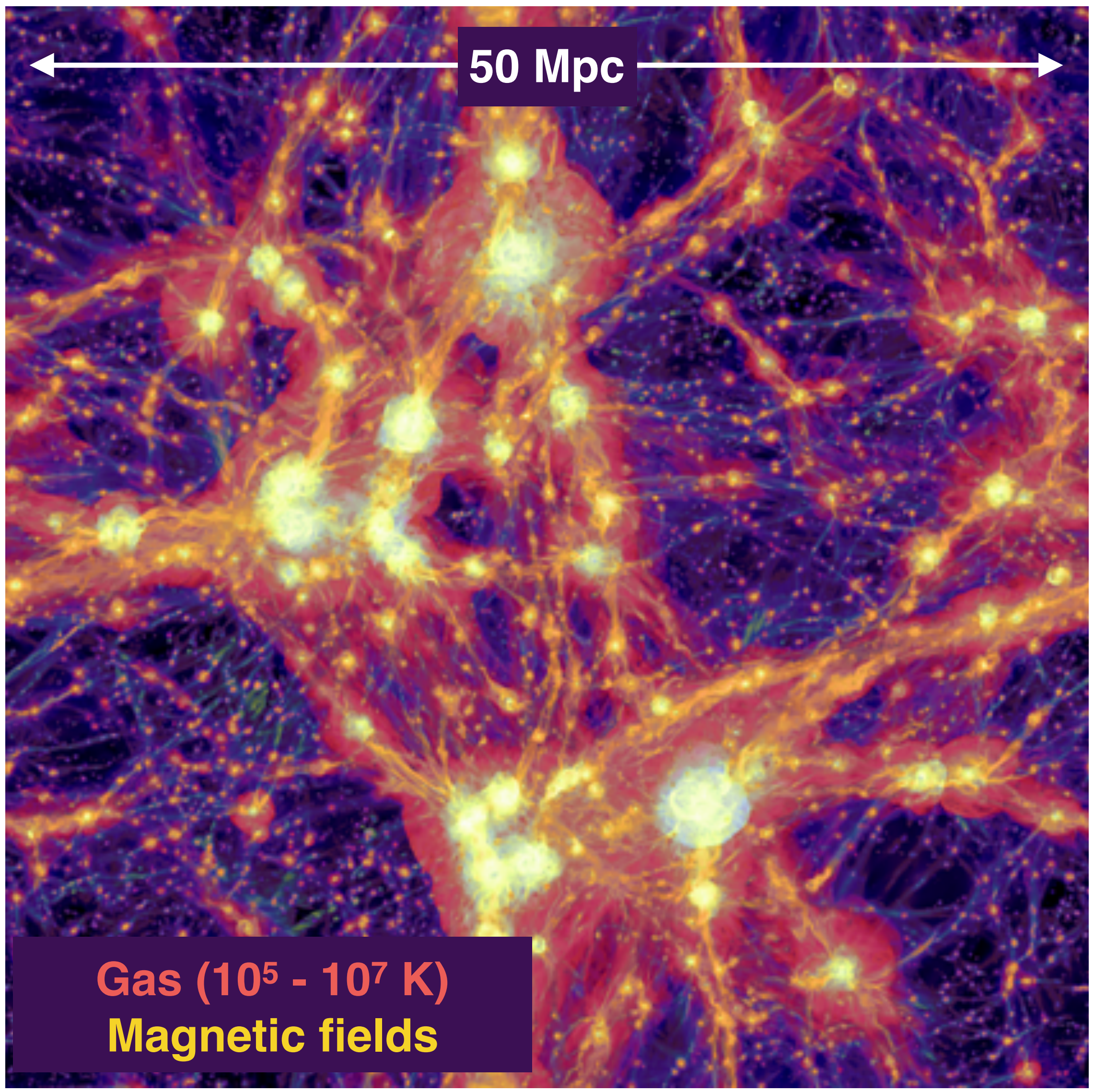


Cosmic filaments lighting up in radio?

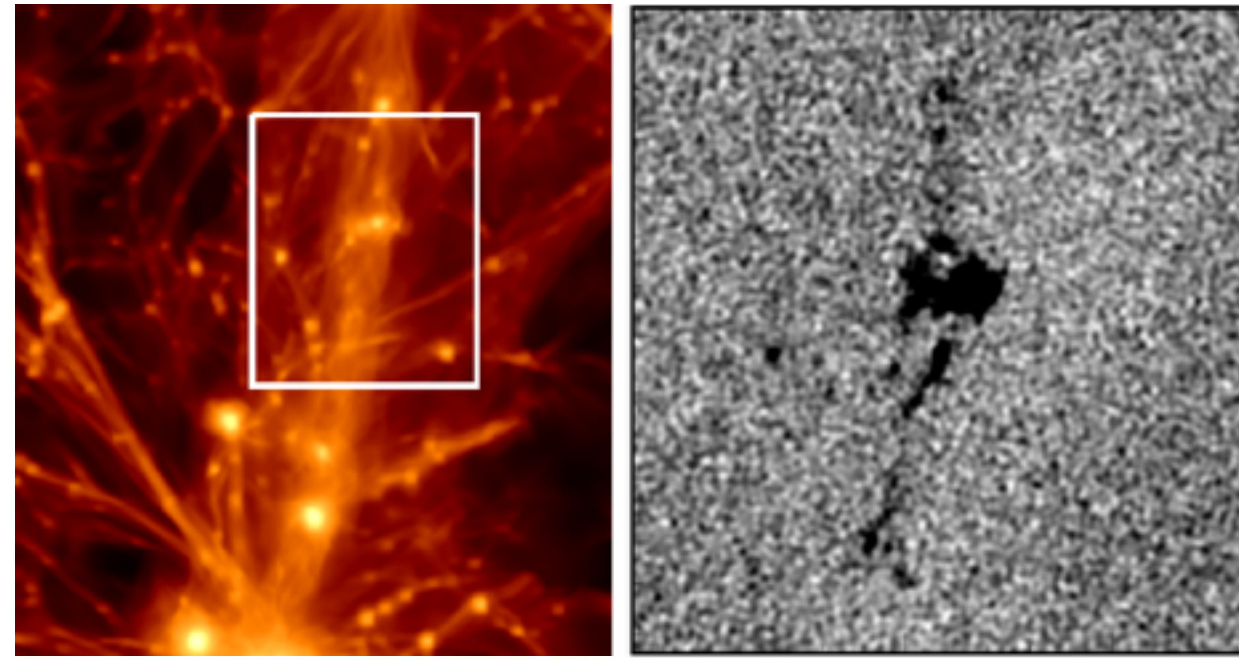


Courtesy: F. Vazza

Cosmic filaments lighting up in radio?

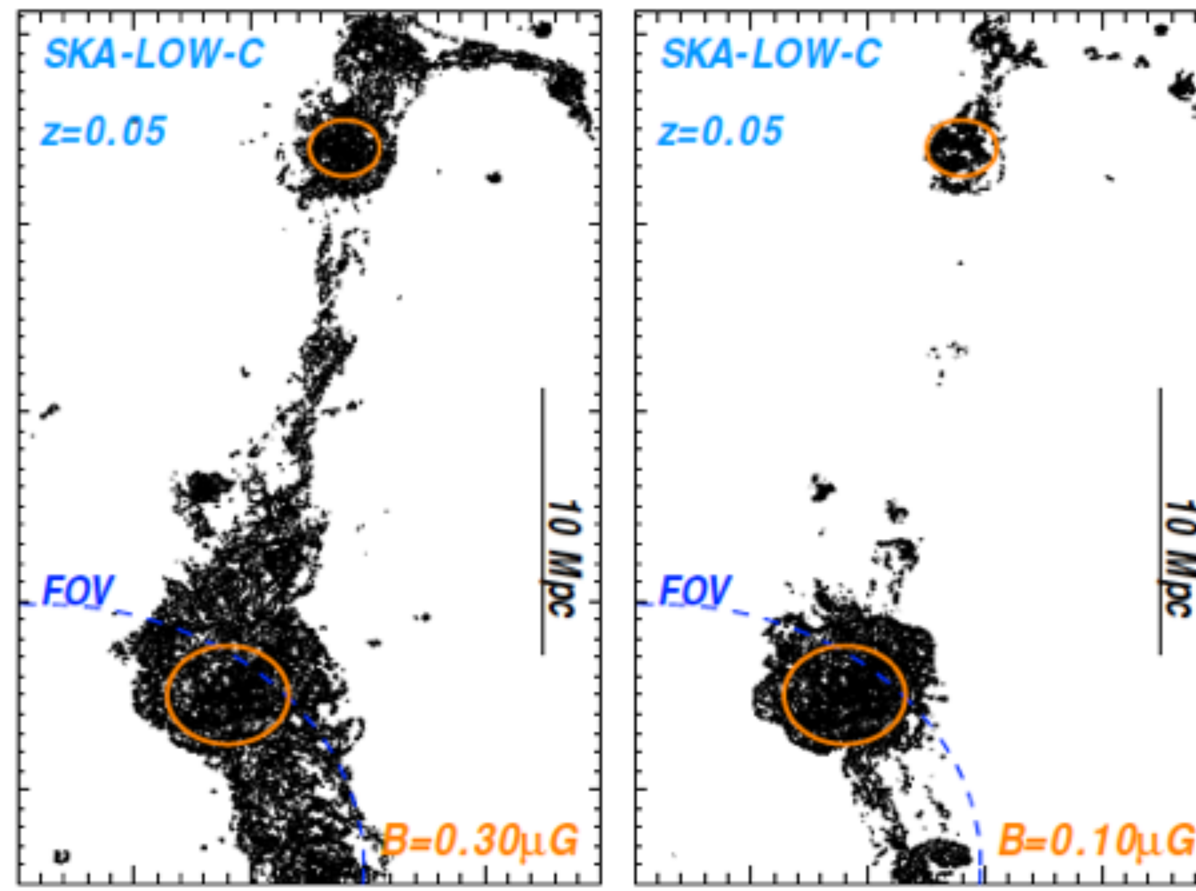


Courtesy: F. Vazza



Simulated filament

Synthetic SKA observations



Vazza+ 15

Conclusions

- **Exciting science expected with SKA and its pathfinders / precursors**
- **SKA: all-science instruments releasing reduced data**
- **Challenging instruments**
- **The community is widening**


A big community at work !
“Advancing Astrophysics with the Square Kilometre Array”, June 2014, Giardini Naxos, Italy